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Supplemental, end-of-day, and sole-source lighting from light-emitting diodes influences growth, morphology, and quality of annual bedding plant seedlings

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SUPPLEMENTAL, END-OF-DAY, AND SOLE-SOURCE LIGHTING FROM LIGHT-EMITTING DIODES INFLUENCES GROWTH, MORPHOLOGY, AND QUALITY OF ANNUAL BEDDING PLANT SEEDLINGS

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Those who labour in the earth are the chosen people of God.--Thomas Jefferson

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ABSTRACT

Randall, Wesley C. M.S., Purdue University, August 2014. Supplemental, end-of-day, and sole-source lighting from light-emitting diodes influences growth, morphology, and quality of annual bedding plant seedlings. Major Professor: Roberto G. Lopez.

Annual bedding plants make up the largest sector of the U.S. floriculture industry. High-quality annual bedding plant seedlings are compact, fully rooted transplants with a large stem caliper and high root dry mass. However, production usually occurs in late winter or early spring when the daily light integral (DLI) is as low as 1 to 5 $mol \cdot m^{-2} \cdot d^{-1}$ in northern latitudes. Therefore, supplemental lighting (SL) is often used to increase the DLI to a recommended 10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$. The objectives of this study were to: 1) quantify the effects of SL from three light-emitting diode (LED) sources of different light qualities and high-pressure sodium (HPS) lamps; 2) quantify the effects of end-of-day (EOD) light from incandescent and compact fluorescent lamps, LEDs of low, medium, and high red:far-red light ratios, or mixed red:blue:far-red ratios (Expt. 2); and 3) quantify the effects of ambient light and SL from LEDs, HPS, and plasma (PL) lamps in a greenhouse, and the effects of sole-source light (SS) from LEDs with two different light qualities in a growth chamber vertical production system (Expt. 3) on seedling growth, morphology, quality, and subsequent flowering. Supplemental light proportions (%) from LEDs (Expt. 1 and 3) ranged from 100:0 to 70:30 red:blue light, and EOD (Expt. 2) LED light

proportions ranged from 100:0 to 50:50 red:far-red or 100:0:0 to 0:100:0 and 62:33:5 red:blue:far-red light. In Expt. 1, stem elongation of *Catharanthus*, *Celosia*, *Impatiens*, *Petunia*, *Tagetes*, *Salvia*, and *Viola* seedlings was reduced 9%–55% under 85:15 red:blue LEDs compared to HPS lamps. In Expt. 2, stem elongation of *Petunia* seedlings after 21 d of EOD light was reduced up to 48% under LEDs providing a red:far-red light ratio ≥4.5 compared to ≈0.9; and 10%–11% under 100:0:0, 75:25:0, and 25:75:0 red:blue:far-red LEDs compared to 62:33:5 red:blue:far-red LEDs. In Expt. 3, stem elongation of *Pelargonium*, *Petunia*, and *Tagetes* was reduced up to 79% under SS compared to HPS lamps. Quality index, a quantitative measurement of quality, of *Petunia* was 44%–129% greater for seedlings grown under all light treatments compared to ambient solar light (control). Additionally, with the exception of *Impatiens*, time to flower was similar or reduced for seedlings propagated under light treatments compared to the control. Overall, the results obtained from these experiments indicate that SL, EOD lighting, and SS can be used to enhance seedling growth, morphology, and quality without substantially delaying subsequent flowering of the annual bedding plant species tested.

INTRODUCTION

Photomorphogenesis

One of the most important environmental factors influencing plant growth is light. Light is the driving force of photosynthesis, phototropic movements, and photomorphogenesis (Schäfer, 2006). Growth, development, and differentiation in plants involve photomorphogenic responses that operate independently of photosynthesis (Withrow, et al. 1957; Mohr, 1964). For example, stomatal opening and stem elongation are both photomorphogenic responses that are influenced by blue (B) light. These light responses are controlled by light-sensitive proteins called photoreceptors (Briggs and Olney, 2001).

Phototropins and cryptochromes are photoreceptors that control phototropism, stomatal opening, and stem elongation. One study identified that phot1 and phot2 affect stomatal opening in the presence of B light where double mutant phot1 and phot2 *Arabidopsis thaliana* (L.) Heynh. plants did not respond while single mutants responded to B light (Kinoshita et al. 2001). Mao et al. (2005) demonstrated that cry1 and cry2 regulate stomata opening and closing and function additively with phototropins where cry1cry2phot1phot2cop1 triple mutants were open as wide as the cop1 mutant under B light.

Cryptochrome 1 (cry1) and 2 (cry 2) are photoreceptors that regulate stem elongation in *Arabidopsis* exposed to B light (Cashmore et al., 1999). Additionally, phototropins such as phototropin 1 (phot1) and 2 (phot2) respond to B light and regulate phototropism and stomatal opening (Briggs and Christie, 2002). Phytochromes are photoreceptors similar to phototropins and cryptochromes; and are responsible for red (R) and far-red (FR) light responses including germination, seedling de-etiolation, stem elongation, floral induction, and neighbor perception and avoidance (Withrow et al. 1957; Mohr, 1964; Fankhauser, 2001; Franklin and Whitelam, 2005). Shade avoidance is another phytochrome mediated response mechanism to avoid shading, crowding, and competition by other plants (Franklin, 2008). The "shade avoidance syndrome" is a term related to the collective response of shade-avoiding species to low R:FR, and is characterized by stem and leaf elongation. However, shade-tolerant species have adapted to optimize photosynthetic efficiency under low light intensities through a variety of means including thinner leaves, increased chlorophyll content, and lens-shaped epidermal cells (Boardman, 1977; Middleton, 2001). Shade tolerance and avoidance have been proposed to be influenced by multiple phytochromes (López-Juez et al., 1992; Smith and Whitelam, 1997). Somers et al. (1991) showed that six long hypocotyl groups of *Arabidopsis* all had long hypocotyls when grown under white light. Using *Escherichia coli*, phyA, B, and C were isolated in the different groups showing a lack of phyB. Similarly, in their 1992 study, López-Juez et al. demonstrated that a long hypocotyl mutant of *Cucumis sativus* L. lacked phyB, a light-stable phytochrome involved in hypocotyl elongation and cotyledon opening and expansion. The interaction of FR light and ethylene in *Helianthus annuus* L. indicated that as the ratio of R:FR decreased from

4.6 to 0.8, ethylene levels were lower in both hypocotyls and internodes, and hypocotyls were as much as twice as long compared to high R:FR ratios (Kurepin et al., 2007). Lund et al. (2007) showed that stem elongation in *Chrysanthemum ×morifolium* Ramat. 'Coral Charm' increased when treated with artificial twilight and end-of-day (EOD) FR. As the ratio of R:FR light decreased from 2.4 (control) to 0.7 (artificial twilight) and 0.4 (EOD FR), stem elongation increased up to 68% above the control. Using FR light and EOD lighting, Chia and Kubota (2010) investigated light quality and dose requirements for hypocotyl elongation in *Solanum lycopersicum* L. 'Aloha' rootstocks. Hypocotyl elongation for plants grown under a R:FR of 0.47 increased by 20% compared to the untreated control, and hypocotyl elongation under a R:FR of 0.05 increased by 44% compared to the untreated control.

Photoperiodism in plants is the requirement of a certain number of hours of darkness that triggers certain developmental responses (Garner and Allard, 1920; Craig and Runkle, 2012). A reduction in R:FR can induce flowering in photoperiodic long day plants (LDP). For example, *Petunia multiflora* 'Easy Wave White' and *Antirrhinum majus* L. 'Liberty Classic Cherry', are LDPs that were shown to flower when R:FR ranged from 0.66 to 1.07 (Craig and Runkle, 2012). Similarly, *Arabidopsis* plants deficient in phyB (hy3 mutant) flowered only slightly earlier than wild-type plants regardless of the ratio of R:FR light (Halliday et al., 1994). The added effect of adding hy3 mutations and decreasing the R:FR ratio in normally late-flowering plants resulted in earlier flowering. Additionally, a study by Devlin et al. (1998) demonstrated that phyE in addition to phyA and phyB functions to regulate flowering time and stem elongation in *Arabidopsis*. Under control conditions consisting of an 8-h photoperiod, phyAphyBphyE

seedlings flowered 11 d earlier than the phyAphyB seedlings. However, EOD FR treatments resulted in plants flowering at roughly the same time, indicating that phyE plays some role in regulating time to flower.

Light quality can also influence germination and stomatal development of certain species. For example, R light promotes germination of *Lactuca sativa* L., while FR light inhibits germination (Borthwick et al., 1954). Ninety percent of seed under R light germinated, but only 7% germinated under FR light. Additionally, phyA promotes stomata development in *Arabidopsis* under FR light, while phyB promotes stomata development under R light. It was also determined that phytochrome and chryptochrome interact, where cry1, cry2, phyA, and phyB act together to promote stomatal development. When *Arabidopsis* were exposed to B plus FR light, the stomatal index (SI; guard cells per total epidermal cells) was reduced in the cry1cry2phyAphyB mutant plants compared to the wild type (Kang et al., 2009). Additionally, Folta and Spalding (2001) demonstrated that cry2 and phototropins can effect stem elongation in *Arabidopsis*. The study showed that inhibition of hypocotyl growth occurs as quickly as 30 s after seedlings were irradiated with B light. Another study used B LEDs as a way to control stem elongation in *Dendranthemum* ×*grandiflorum* Kitam. 'Ragan'. Plants were grown in a growth chamber under 12 h of fluorescent (FL) lamps plus an additional 4-h night break of either FL or B LED lighting. Internode elongation was reduced by as much as 60% for plants grown under the B light treatment compared to the control (Shimizu et al., 2006). Light quality also has a major role in photomorphogenic responses including cell growth, crop yield, and physiological and morphological quality (Johkan et al. 2010 and XiaoYing et al. 2011).

Annual Bedding Plants

Annual bedding plant sales totaled $3.6 billion in 2012 according to the United States Department of Agriculture (2014), higher than any other sector in the floriculture industry. Annual bedding plants are commonly propagated from seed or shoot-tip cuttings (young plants), and were valued at $585 million in 2012 (USDA, 2014). Traditionally, bedding plant seedlings were sown into undivided flats before they were manually transplanted into the finish container. However, seedlings would quickly become crowded leading to uneven seedlings that were excessively tall as a result of the shade-avoidance response. Additionally, because all plants were grown together, root system damage was common. The use of plug trays has alleviated many of the problems caused by traditional seed trays. During plug production, seeds are sown into trays that are partitioned into specialized cells, ranging from 50 to 800 cells per tray. Seedlings are evenly spaced and root systems are able to develop independently; therefore crowding, excessive stem elongation, and root damage are reduced compared to traditional seed flats (Armitage and Kaczperski, 1994).

Propagation typically occurs during late winter and early spring when the average photosynthetic daily light integral (DLI) is low, ranging from 5 to 10 $mol \cdot m^{-2} \cdot d^{-1}$ outdoors and 1 to 5 $mol \cdot m^{-2} \cdot d^{-1}$ in greenhouses in northern latitudes (Klopmeyer et al. 2003; Korczynski et al., 2002; Lopez and Runkle, 2008;Styer, 2003). The DLI is the rate of photosynthetically active radiation (PAR; 400 to 700 nm) delivered to plants over a 24-h period (Faust et al. 2005; McCree, 1972). For many ornamental bedding plants, overall quality increases as DLI increases. One study demonstrated that as DLI increased, shoot dry mass in *Petunia ×hybrida* Vilm.-Andr. ‘Madness Red’ and *Viola ×wittrockiana*

Gams. 'Delta Premium Yellow' seedlings increased linearly. For example, when supplemental lighting (SL) providing a *PPF* of 90 μmol·m^{-2}·s^{-1} was used during the last two-thirds or entire seedling stage, shoot dry mass and the number of leaves increased compared to SL in the first one-third stage or with photoperiodic lighting. Additionally, flowering was accelerated when SL was provided during the last two-thirds or entire seedling stage compared to SL provided during the first one-third seedling stage or under photoperiodic light (Oh et al., 2010). Similarly, *Angelonia angustifolia* Benth. 'AngelMist White Cloud', *Nemesia fruticans* (Thunb.) Benth. 'Aromatica Royal', *Osteospermum ecklonis* (DC.) Norl. 'Voltage Yellow', and *Verbena* ×*hybrida* Ruiz 'Aztec Violet' cuttings were propagated in a greenhouse with a DLI ranging from 1.2 to 12.3 mol·m^{-2}·d^{-1}. Time to first open flower decreased by 23 and 19 d for *Angelonia* and *Osteospermum*, respectively, as propagation DLI increased from 1.2 to 12.3 mol·m^{-2}·d^{-1}. Final height of all species except *Verbena* was also reduced as DLI increased. For instance, *Angelonia* and *Osteospermum* height was reduced by 6.1 and 3.5 cm, respectively, as propagation DLI increased from 1.2 to 12.3 mol·m^{-2}·d^{-1} (Hutchinson et al., 2012).

Studies have shown that low DLI leads to diminished quality for young and finished plant growth, and that a DLI of 10 to 12 mol·m^{-2}·d^{-1} is a desirable minimum recommendation for young plant production (Faust et al., 2005; Lopez and Runkle, 2008; Oh et al. 2010; Hutchinson et al., 2012; Currey et al., 2012; Currey and Lopez, 2013). Consequently, the only way to appreciably increase DLI during winter and early spring propagation is through the use of SL (Oh et al. 2010).

Supplemental Lighting

High-intensity discharge lamps (HID) are commonly used for SL in greenhouses. Two of the most common types of HID lamps are high-pressure sodium lamps (HPS) and metal halide (MH) lamps (Spaargaren, 2001). High-pressure sodium lamps have traditionally been used for SL in greenhouses; however, they primarily emit light in the range of 565 to 700 nm which is primarily yellow (565 to 590 nm), orange (O; 590 to 625 nm), and R (625 to 700 nm), with a peak at 589 nm. The efficiency of HPS lamps is only ≈25% to 30% with a lifespan ≈10,000 luminous hours. Energy not converted to light (70% to 75%) is emitted as radiant heat energy causing the surface of HPS lamps to reach temperatures as high as 450 °C, which requires the separation of lamps from plants to prevent leaf scorch (Fisher and Both, 2004; Nelson, 2012; Sherrad, 2003; Spaargaren, 2001). One study compared the energy balance and efficiency of HPS lamps and light-emitting diodes (LEDs) to quantify the relative efficiency of both systems. A standard 400-W HPS lamp was compared to a water-cooled HPS lamps with heat-resistant, glass jackets containing 4-mm or 9-mm water thickness cooled to either 40 or 60 °C, and LED arrays of (%) 75:25 R:B light. Results indicated that the control HPS lamp and LEDs had similar electrical conversion efficiencies near 27% based on their PAR output and that neither of the water-cooled HPS lamps were as efficient in their total electrical conversion efficiency when accounting for the water re-circulating pump (Shimomachi et al., 2006). Another study compared the photon efficiency of two double-ended HPS lamps, five mogul-base HPS lamps, ten LED fixtures, three ceramic MH, and two FL lamps. The two most efficient LEDs and HPS lamps had similar conversion efficiencies of 1.66 to 1.70 $\mu mol \cdot J^{-1}$; but the best MH and FL lamps had efficiencies of only 1.46 and

0.95 μmol·J^{-1}, respectively. However, the study also demonstrated that the initial capital cost of LEDs can be five to ten times greater than that for HPS lamps, and that the 5-year cost of electricity plus fixture cost per mole of photons can be up to 2.3 times greater for LEDs compared to HPS lamps (Nelson and Bugbee, 2014).

A number of alternatives to HID lamps have been introduced, including plasma (PL) and high-intensity LEDs (Sager and Wheeler, 2012). Plasma lamps are electrodeless light sources that emit a continuous light spectrum by exciting sulfur or halide molecules in the lamp using an excitation source such as a magnetron or radio frequency generator. Unlike HPS lamps, PL lamps are able to convert up to 70% of the electricity delivered to the lamp into emitted light. However, similar to HPS lamps, PL lamps are capable of reaching temperatures as high as 900 °C to 1200 °C. Although the bulbs are reported to last many years, the excitation sources tend to have short lifespans (Sager and Wheeler, 2012). Alternatively, LEDs have recently been able to achieve light outputs as high as HID lighting methods (Morrow, 2008).

Light-emitting diodes are solid-state semi-conducting diodes that can emit narrow spectra of light from 250 to ≥1000 nm that have been considered for use as sole-source light (SSL) and SL (Barta et al. 1992; Bourget, 2008; Bula et al. 1991; Massa et al. 2008). Light-emitting diodes are also desirable because they do not radiate heat towards the plant canopy, allowing LEDs to be placed close to a crop. Heat is instead radiated off the back of the diode where electricity runs across the diode junction, which can diminish the life and efficiency of the LED if not properly dissipated. Therefore, effective heat dissipation without significant shading is necessary to take full advantage of LEDs for greenhouse production (Bourget, 2008; Christensen and Graham, 2009). A study by

Currey and Lopez (2013) used forced-air cooled LEDs as SL to grow annual bedding plant cuttings and found that the fans used to cool the arrays accounted for 37% to 45% of their energy consumption; therefore, using 9% to 35% more energy than the HPS lamps used in the study. However, without fans, the LED arrays used 15% to 40% less energy than HPS lamps. Conversely, another study used passively cooled LEDs compared to HPS lamps and found that energy consumption was reduced by 48% to 59%. As a result of using passively cooled LEDs, solar radiation was blocked by ≈50% because of the increased size of the fixtures (Randall and Lopez, 2014).

Light-emitting diodes offer the ability to test wavelength combinations to manipulate plant morphology, control plant stature, and accelerate juvenility (Folta and Childers, 2008; Stutte, 2009). Wavebands most frequently used for studies of plant growth and development are B (450 nm), R (660 nm), and FR (730 nm). Additionally, LEDs have an estimated life of ≥ 50,000 luminous hours and an efficiency rating that doubles every two years, following Haitz's Law (Bourget, 2008; Morrow, 2008; Steigerwald et al. 2002). For example, in 2006, B LEDs were rated to be 11% efficient, and in 2014, 49% efficient (Massa et al., 2006; Nelson and Bugbee, 2014; Philips Lumileds, 2011). In addition to their increasing efficiency, the ability to test specific wavelengths of light is important because it has been shown that light quality has a significant effect on plant growth, development, and physiology (Brown et al., 1995; Sage, 1992; Smith, 1982).

A number of studies have looked at the use of LEDs for SL and SSL in horticulture because of their versatility and ability to emit narrow light spectra. They have been used as low-intensity point-source light for photoperiodic lighting as well as planar

and vertical SL (Schuerger et al. 1997; Massa et al. 2005; Massa et al. 2006; Craig and Runkle, 2012; Currey et al. 2013). Each configuration has advantages and disadvantages. For example, point-source lighting requires lamps to be placed some distance from the canopy to achieve even light distribution resulting in a loss of light intensity. However, they are easily retrofitted for greenhouse use because many of them are made to fit into traditional incandescent bulb fixtures. Alternatively, vertical LED arrays allow for intra-canopy lighting, which is especially useful for taller crops while planar-style LED arrays offer more uniform coverage than point-source lighting and are often used for SL and SSL (Morrow, 2008).

Sole-source LED Lighting in Horticulture

One study compared growth and photomorphogenic effects on *Capsicum annuum* L. 'Hungarian Wax' grown in a growth chamber under a 12 h photoperiod supplied by 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ *PPF* from either MH or three LED light treatments providing (%) 100:0 or 99:1 R:FR, or 99:1 R:B light (B light delivered from FL lamps) for 21 d (Brown et al. 1995). The MH lamps provided 20% of the *PPF* between 400 and 500 nm, 56% between 500 and 600 nm, and 24% between 600 and 700 nm. The 99:1 R:FR light resulted in significant stem elongation and plants were 90% longer than the MH control plants. Shoot and root dry mass were also lower for plants grown under the FR treatment compared to the MH control, but not as low as the R light treatment alone. The number of leaves per plant was greatest for plants grown under the 99:1 R:B light or MH compared to the 100:0 and 99:1 R:FR LEDs.

The responses of *Abelmoschus esculentus* L. Moench. 'Clemson Spineless' and 'Emerald' and *Abelmoschus moschatus* ssp. *tuberosus* Span. Borss., both short day plants

was studied when plants were grown under LEDs with R, B, and green (G) light. Plants were grown in growth chambers providing different photoperiods with a *PPF* of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from FL plus 4 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from monochromatic R, B, or G LEDs. Experiment one (Expt. 1) light treatments consisted of a 6-h photoperiod (control) or a 12-h day extension. Experiments two and three (Expt. 2; Expt. 3) consisted of an 8-h photoperiod (control) or a 4-h night interruption preceded and followed by 6 h of darkness. In Expt. 1, the control resulted in flower buds appearing on lower nodes than on plants receiving day extension from R or B LEDs. The appearance of buds was also significantly delayed under R light compared to B light. In Expt. 2, night break with R LEDs delayed the appearance of buds and flowering similarly to Expt. 1. Night break with B LEDs did not delay flowering for either cultivar. It did, however, have a weaker effect on night break treatments than day extension treatments. Expt. 3 compared B, G, and R LEDs and demonstrated that flower buds developed faster on plants grown under B light than G or R light. Night break with R light suppressed flowering more than B or G light, but G light suppressed flowering more than B light (Hamamota and Yamazaki, 2009).

Ohashi-Kaneko et al. (2006) placed *Oryza sativa* L. 'Sasanishiki' and 'Nipponbare' under LEDs with (%) 100:0 and 80:20 R:B light to compare biomass production. Plants were grown for 56 d in an environmentally controlled chamber with a 12 h photoperiod providing a total *PPF* of 380 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (DLI ≈16.4 $mol \cdot m^{-2} \cdot d^{-1}$). Four plants per treatment were harvested weekly between 21 and 56 d after germination. Both cultivars had higher biomass production when supplemented with B light compared to the 100:0 R:B treatment. For example, total plant dry weight was 20% and 33% higher

for ‘Sasaniski’ and ‘Nipponbare’, respectively. Additionally, total leaf area for ‘Sasaniski’ and ‘Nipponbare’ was 30% and 35% higher than for plants grown under 100:0 R:B conditions. Similarly, when *Lactuca sativa* ‘Banchu Red Fire’ was grown under 50:50 R:B and 0:100R:B LEDs fresh weight increased by 29% and 83%, respectively, compared to plants grown under white FL (Johkan et al. 2010).

The response of *Tagetes erecta* L. ‘Orange Boy’ and *Salvia splendens* F. Sello ex Ruem & Schult. ‘Red Vista’ was quantified under monochromatic and mixed radiation treatments receiving a *PPF* of 90 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 16 h daily from FL, R, B, and FR LEDs. After 25 d, dry mass of *Tagetes* was greatest in the presence of monochromatic R, FL and R, or FL, but reduced with monochromatic B light. *Salvia*, however, had significantly higher dry mass when plants were grown in the presence of FL plus B light, FL plus R light, and FL plus FR light. Stem length of *Tagetes* was longest when grown under monochromatic B light with an average height ≈25 cm compared to the FL control with an average height ≈10 cm. Visible bud count also increased when plants were exposed to FR light while bud formation appeared to be inhibited by both monochromatic R or B light in both species (Heo et al., 2002).

A later study using the same light intensity and duration as above with a 1:1 ratio for mixed light found that dry mass of three annual species (*Ageratum houstonianum* Mill. ‘Blue Field’, *Tagetes* ‘Orange Boy’, and *Salvia* ‘Red Vista’) increased when plants were grown under R:B and FL compared to B:FR and R light and that stem length was shortest for plants grown under R:B light compared to R and R:FR light. For example, dry mass of *Ageratum* was nearly double after 21 d for plants grown under R:B and FL compared to B:FR and R:FR treatments. Stem length of *Tagetes* and *Salvia* was 44% to 64% shorter

for plants grown under R:B and FL compared to plants grown under B:FR and R:FR light (Heo et al. 2006).

Another study included seedlings of *Impatiens walleriana* Hook f.'SuperElfin XP Red', *Petunia* 'Wave Pink', *Solanum* 'Early Girl' under SSL delivering a *PPF* of 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (DLI ≈9 $mol \cdot m^{-2} \cdot d^{-1}$) for 18 h from LEDs providing 10% B and 10% G with (%) 20:30:30, 0:80:0, 0:60:20, 0:40:40, 0:20:60; and 0:0:80 O (596 nm), R (634 nm), and hyper-red (HR; 664) light. Leaf number of all species was similar among treatments. Leaf area was also similar among all treatments and species, except *Solanum,* which was lower under 0:0:80 O:R:HR light than under three of four treatments providing ≥30% R light. The effect of treatment on height and dry mass, however, varied by species. *Solanum* and *Tagetes* height was reduced by 18% and 13% shorter under 0:40:0 than 0:80:0 O:R:HR light, respectively, but similar to other light treatments. Shoot dry mass of *Solanum* was 25% to 40% greater under 0:60:20 O:R:HR LEDs compared to 0:40:40, 0:20:60, or 0:0:80 O:R:HR LEDs (Wollaeger and Runkle, 2013).

Supplemental LED Lighting for Horticulture

Most research has focused on using LEDs as SSL in growth chambers. However, little work has been done using LEDs for SL in greenhouse production, until recently. One such experiment compared LEDs to HPS lamps for hydroponically grown *L. sativa* var. *capitata*. Supplemental lighting was provided 2 h before sunset and another 8.5 hours after sunset to achieve an 18 h photoperiod. HPS lamps provided an average *PPF* of 71 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and LEDs an average *PPF* of 36 $\mu mol \cdot m^{-2} \cdot s^{-1}$ over 4 weeks, a DLI of ≈2.6 and 1.3 $mol \cdot m^{-2} \cdot d^{-1}$, respectively. Shoot dry mass, β-carotene, chlorophyll a and b, neoxanthin, lutein, and antheraxanthin were statistically similar for both HPS and LED

light treatments, despite LEDs providing roughly half the irradiance of HPS lamps (Martineau et al. 2012).

Another study compared LEDs and HPS lamps as SL for *Euphorbia pulcherrima* Willd. ex Klotzsch 'Christmas Spirit', 'Christmas Eve', and 'Advent Red' crops to control stem elongation. Plants were provided a supplemental *PPF* of 100 ± 20 μmol·m^{-2}s^{-1} for a 10 h photoperiod. HPS lamps contained roughly 5% B light, while LEDs provided (%) 80:20 R:B light. All cultivars grown under the LED light treatment were 20% to 34% shorter than those grown under HPS lamps. Additionally, leaf and bract area, relative chlorophyll content, and total dry matter accumulation were lower for plants grown under LEDs. For example, leaf area was reduced by 40% and 46% while bract area was reduced by 61% and 49% for 'Christmas Spirit' and 'Christmas Eve', respectively. However, time to visible cyathia was not significantly different between LED and HPS lamps. These results indicate that LEDs could potentially be used as a way to reduce stem elongation without the use of chemical plant growth regulators (Islam et al. 2012).

Similarly, cuttings of *Impatiens hawkeri* W. Bull 'Celebrette Frost', *Pelargonium* ×*hortorum* L.H. Bailey 'Designer Bright Red', and *Petunia* 'Suncatcher Midnight Blue' were grown under a 16 h photoperiod supplemented by HPS lamps and LEDs with varying proportions (%) of R:B light (100:0, 85:15, or 70:30) delivering a *PPF* of 70 μmol·m^{-2}·s^{-1}. After 14 d under SL, there were no significant differences among *Impatiens* and *Pelargonium* grown under any SL source. Conversely, stem length of *Petunia* grown under 100:0 R:B LEDs was reduced by 11% compared to HPS lamps; and leaf dry mass,

root dry mass, and root:shoot ratio of cuttings grown under 70:30 R:B LEDs increased by 15%, 36%, and 24%, respectively, compared to HPS lamps (Currey and Lopez, 2013).

Another study compared seedlings of *Antirrhinum majus* L. 'Rocket Pink', *Catharanthus roseus* L. G. Don 'Titan Punch', *Celosia argentia* L. var. *plumosa* L. 'Fresh Look Gold', *Impatiens walleriana* 'Dazzler Blue Pearl', *Pelargonium* 'Bullseye Scarlet', *Petunia* 'Plush Blue', *Salvia* 'Vista Red', *Tagetes patula* L. 'Bonanza Flame', and *Viola* 'Mammoth Big Red' grown under SL of 100 $\mu mol \cdot m^{-2}s^{-1}$ delivered from HPS and LEDs of varying proportions (%) of R:B light (100:0, 85:15, 70:30) for 16 h. After 28 d under treatment, height of *Catharanthus*, *Celosia*, *Impatiens*, *Petunia*, *Salvia*, *Tagetes*, and *Viola* was reduced by 31%, 29%, 31%, 55%, 9%, 20%, and 35%, respectively, for seedlings grown under 85:15 R:B LEDs compared to HPS lamps. Additionally, stem caliper of *Antirrhinum*, *Pelargonium*, and *Tagetes* increased by 16%, 8%, and 13%, respectively, under 85:15 R:B LEDs compared to HPS lamps. Quality index, an integrated qualitative measurement (Currey et al., 2013), of *Petunia*, *Salvia*, and *Viola* was greatest under LEDs compared to HPS lamps. Quality index of all other species except *Celosia* was similar under LEDs and HPS lamps, whereas *Celosia* quality index was greatest under HPS lamps (Randall and Lopez, 2014).

End-of-day and Photoperiodic LED Lighting in Horticulture

End-of-day and photoperiodic light is another method used to improve quality of ornamental bedding plants. Providing specific combinations of R and FR light during twilight or the end of the photoperiod using EOD lighting is known to influence stem length and flowering in a number of species (Blom et al., 1995; Chia and Kubota, 2010; Craig and Runkle, 2013; Decoteau et al., 1988; Ilias and Rajapakse, 2005; Kasperbauer,

1971). For example, one study demonstrated that EOD R or FR lighting on *Petunia* 'Countdown Burgundy' affected time to flower without adversely affecting stem length in FR-deficient environments. Plants were grown under greenhouse films that were either clear (control; R:FR ≈1.05), absorbed FR light (R:FR ≈1.51), or absorbed R light (R:FR ≈0.67); and were given a 15 min dose of R or FR light at the end of a 10.5 h photoperiod. Stem length of plants grown under EOD FR light increased by 7%, 19%, and 64% under the control, R, and FR films, respectively; however, height under the FR film was 25% shorter than control plants receiving no EOD lighting. Additionally, EOD R or FR light did not affect flowering under the control and FR film (Ilias and Rajapakse, 2005)

A separate study used seedlings of *Cucurbita maxima* Duchesne ×*Cucurbita moschata* Duchesne 'Tetsukabuto' to compare the effects of EOD FR light from movable and stationary LED fixtures delivering 4.5 and 6.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively, for 5 d. Movable LEDs either made one pass or four passes at a faster speed over the plant canopy to achieve a FR dose of 4.0 $mmol \cdot m^{-2} \cdot d^{-1}$, matching the dose of the stationary LEDs. Hypocotyl elongation was similar under movable LEDs to stationary LEDs, regardless of traveling speed, and were 55% to 69% greater than the non-treated control (Yang, et al., 2012).

Another study grew *Chrysanthemum* ×*morifolium* 'Adiva Purple', *Dahlia hortensis* 'Dahlinova Figaro Mix', and *Tagetes erecta* 'American Antigua Yellow' in a greenhouse under a 9 h photoperiod created by black cloth with or without a 4 h night interruption from incandescent lamps or LEDs with a R:FR light ratio ranging from ≈0.05 to ≈147.3. Flowering of *Chrysanthemum* was not inhibited by a R:FR ≤0.28, but was reduced when R:FR ≥0.66. Alternatively, time to flower of *Dahlia* was incomplete when

the R:FR was ≈0.05 with and without night interruption, but time to flower was similar for the other night interruption treatments. Additionally, stem length of all species increased quadratically as the R:FR of the night interruption increased up to ≈0.66 (Craig and Runkle, 2013).

Further research is needed to gain a better understanding of the cultural and environmental requirements of seed produced annual bedding plants. Previous research has shown that a balance of R and FR light in the phytochrome apparatus impacts morphological responses such as germination, stem elongation, and flowering. Blue light is also an important morphological factor that has been shown to affect stem elongation, stomatal opening, and phototropism in the cryptochrome and photropin systems. Light-emitting diodes have the potential to improve the production of annual bedding plants because of their versatility and the ability to provide customized, narrow-spectrum light regimes. This is especially important because of demands placed on propagators to produce high-quality, compact seedlings in addition to meeting strict flowering requirements for finished plants. For this reason, more research is needed to investigate the effects of LED SL and SSL in annual bedding plant production.

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COMPARISON OF SUPPLEMENTAL LIGHTING FROM HIGH-PRESSURE SODIUM LAMPS AND LIGHT-EMITTING DIODES DURING BEDDING PLANT SEEDLING PRODUCTION

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Abstract

Annual bedding plant seedlings or plugs are considered high-quality when they are compact, fully rooted transplants with a large stem caliper and high root dry mass. Greenhouses in northern latitudes rely on supplemental lighting (SL) from high-pressure sodium lamps (HPS) during winter months to achieve high-quality, finished plugs. Light-emitting diodes (LEDs) offer higher energy efficiencies, a long operating life, and precise waveband specificity that can eliminate wavebands not considered useful. Seedlings of *Antirrhinum*, *Catharanthus*, *Celosia*, *Impatiens*, *Pelargonium*, *Petunia*, *Tagetes*, *Salvia*, and *Viola* were grown at 21 °C under a 16-h photoperiod of ambient solar light and SL of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from either HPS lamps or LED arrays with varying proportions (%) of red:blue light (100:0, 85:15, or 70:30). Height of *Catharanthus*, *Celosia*, *Impatiens*, *Petunia*, *Tagetes*, *Salvia*, and *Viola* was 31, 29, 31, 55, 20, 9, and 35% shorter, respectively, for seedlings grown under the 85:15 red:blue LEDs compared to those grown under HPS lamps. Additionally, stem caliper of *Antirrhinum*, *Pelargonium*, and *Tagetes* was 16, 8, and 13% larger, respectively, for seedlings grown under the 85:15 red:blue LEDs compared to seedlings grown under HPS lamps. The quality index (QI), a

quantitative measurement of quality was similar for *Antirrhinum*, *Catharanthus*, *Impatiens*, *Pelargonium*, and *Tagetes* grown under LEDs and HPS lamps. However, it was significantly higher for *Petunia*, *Salvia*, and *Viola* under 85:15, 70:30, and 100:0 red:blue LEDs than under HPS lamps. These results indicate that seedling quality for the majority of the species tested under SL from LEDs providing both red and blue light was similar or higher than those grown under HPS lamps.

Introduction

Annual bedding plant sales for the 15 top-producing states were over $1.4 billion in 2012, the highest of any sector of the U.S. commercial floriculture industry (USDA, 2013). Advancements in production of bedding plant seedlings, also known as young plants or plugs, have led to a large increase in finish plant quality and profitability (Armitage and Kaczperski, 1994; Kuehny et al., 2001). Young plant production occurs in late winter and early spring when the integrated photosynthetic photon flux (*PPF*), or daily light integral (DLI), can be 1 to 5 $mol \cdot m^{-2} \cdot d^{-1}$ or lower during cloudy weather in northern latitudes (Lopez and Runkle, 2008). Previous studies indicate that young and finished plant growth and quality are diminished by low DLI (Currey et al., 2012; Faust et al., 2005; Hutchinson et al., 2012; Lopez and Runkle, 2008; Oh et al., 2010). A DLI of 10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$ has been shown to be a desirable minimum recommendation for growing high-quality young plants (Currey et al., 2012; Lopez and Runkle, 2008; Oh et al., 2010).

Previously, the only way for young-plant producers to appreciably increase ambient greenhouse DLI was to provide SL from high intensity discharge (HID) lights. High-pressure sodium (HPS) lamps are the most commonly used HID light sources, and

several characteristics contribute to their use. However, HPS lamps primarily emit light in the spectral range of 565 to 700 nm, which is primarily yellow (565 to 590 nm), orange (590 to 625 nm), and red (625 to 700 nm), and have a peak at 589 nm. HPS lamps are ≈25 to 30% efficient with a lifespan of 10,000 luminous hours or more. Up to 75% of the energy not converted to light is emitted as radiant heat energy causing the surface of HPS lamps to reach temperatures as high as 450 °C, and requires separation of lamps from plants to prevent leaf scorch (Fisher and Both, 2004; Nelson, 2012; Sherrard, 2003; Spaargaren, 2001).

Light-emitting diode (LED) are solid-state, semi-conducting diodes that can emit narrow spectra of light from ~250 nm to ≥1000 nm and have been considered for use as sole-source and SL (Barta et al., 1992; Bourget, 2008; Bula et al. 1991; Massa et al. 2008). The peak wavelengths of greatest interest for studies of plant growth and development include blue (450 nm), red (660 nm), and far-red (730 nm). Recently, LEDs have achieved an efficiency of 38% (red) to 50% (blue) converting electrical energy to photons (Philips Lumileds, 2011) and have an estimated lifespan of ≥ 50,000 h (Bourget, 2008). Light-emitting diodes offer the ability to test wavelength combinations to manipulate plant morphology and control plant stature (Folta and Childers, 2008; Stutte, 2009).

Light quality has been shown to have a significant effect on plant growth, development, and physiology (Brown et al., 1995; Sage, 1992; Smith, 1982). Previous studies have focused on the use of LEDs as sole-source lighting in highly controlled and enclosed environments (Massa et al., 2008), as a SL source for intercanopy (Dueck et al., 2006; Hovi-Pekkanen et al., 2006; Trouwborst et al., 2010) or overhead (Dueck et al.,

2012) lighting for greenhouse vegetable production, or propagation of ornamental cuttings (Currey and Lopez, 2013). Utilizing LEDs requires determining the best light quality for each crop (Massa et al., 2008).

For example, when *Zantedeschia jucunda* K. Koch 'Black Magic' (calla lily) was grown *in vitro* under a total *PPF* of 80 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of varying proportions of red and blue light from LEDs, stem elongation, but not dry mass, could be manipulated. As blue light increased from 0 to 32 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and red light was reduced from 80 to 48 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (red:blue ratio = 1.5), stem elongation decreased from 10.5 to 8.5 cm (Jao et al., 2005). In a separate study, van Ieperen et al. (2012) grew *Cucumis sativus* L. 'Hoffman Giganta' (cucumber) in growth chambers under LEDs providing a *PPF* of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of either 100:0, 0:100 or 70:30 red:blue light over a 16-h photoperiod. Petiole length of plants grown under 70:30 red:blue LEDs was reduced by 1.0 cm while stomatal density and net leaf photosynthesis increased by 248 mm^{-2} and 1.2 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$, respectively, compared to plants grown under monochromatic red light. Hernández and Kubota (2012) demonstrated the benefits of greenhouse SL on the growth and development of *Solanum lycopersicum* L. 'Komeett' (tomato) seedlings grown under solar DLIs of 8.9 to 19.4 $mol \cdot m^{-2} \cdot d^{-1}$ and LED SL providing a *PPF* of 56 $\mu mol \cdot m^{-2} \cdot s^{-1}$. However, there were no significant differences in shoot dry mass, leaf count, stem diameter, hypocotyl length, leaf area, and chlorophyll concentration among the different LED SL treatments providing red:blue *PPF* ratios of 100:0, 96:4, or 84:16. Another study demonstrated no differences in productivity for greenhouse-grown tomato cultivars 'Komeett' and 'Success' grown under overhead HPS lamps or intracanopy LEDs towers providing 95:5 red:blue light (Gómez et al., 2013).

To our knowledge, no previous studies have quantified the effects of narrow-spectra high intensity LEDs as a SL source for annual bedding plant seedlings. The objectives of this study were to: 1) quantify the effects of SL from three LED sources of different light quality and HPS lamps on seedling growth, morphology, and quality; and 2) determine whether there were any residual effects of SL source on subsequent growth and development after transplant in a common environment.

Materials and Methods

Plant material, culture, and environmental conditions.

Seeds of *Antirrhinum majus* L. 'Rocket Pink', *Catharanthus roseus* L. G. Don 'Titan Punch', *Celosia argentea* L. var. *plumosa* L. 'Fresh Look Gold', *Impatiens walleriana* Hook. f. 'Dazzler Blue Pearl', *Pelargonium ×hortorum* L.H. Bailey 'Bullseye Scarlet', *Petunia ×hybrida* Vilm.-Andr. 'Plush Blue', *Salvia splendens* Sellow ex Roem. & Schult. 'Vista Red', *Tagetes patula* L. 'Bonanza Flame', and *Viola ×wittrockiana* Gams. 'Mammoth Big Red' (Ball Horticulture, West Chicago, IL) were sown into 288-cell (5-mL individual cell vol.) seed trays at a commercial greenhouse (Heartland Growers, Westfield, IN). Upon hypocotyl emergence, trays were placed in a glass-glazed greenhouse with exhaust fan and evaporative-pad cooling, radiant hot water heating, and retractable shade curtains controlled by an environmental control system (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada) at Purdue University, West Lafayette, IN (lat. 40 °N).

All species were placed under a 16-h photoperiod with air temperatures of 21.2 ± 1.7 and 21.7 ± 2.0 °C for *Celosia*, *Petunia*, *Impatiens*, *Tagetes*, and *Viola* (group I) and 20.9 ± 0.96 and 21.3 ± 1.4 °C for *Antirrhinum*, *Catharanthus*, *Pelargonium*, and *Salvia*

(group II). Infrared temperature sensors (OS136, Omega Engineering, Inc., Stamford, CT) recorded seedling leaf temperatures every 30 s and averages were logged every 15 min by a data logger (Maximizer Precision 10). Amplified quantum sensors (LI-190, LI-COR Biosciences, Lincoln, NE) measured solar *PPF* every 30 s and the average of each sensor was logged every 15 min by a data logger (Model CR1000; Campbell Scientific, Inc., Logan, UT). Environmental data are reported in Table 1. Seedlings were irrigated with water-soluble fertilizer (Jack's LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) providing (in $mg \cdot L^{-1}$): 100 N, 10 P, 78 K, 18 Ca, 9.4 Mg, 0.10 B, 0.05 Cu, 0.50 Fe, 0.25 Mn, 0.05 Mo, and 0.25 Zn.

Table 2.1 Average plant temperatures and daily light integral (DLI) under ambient solar daylight supplemented with approximately 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ delivered from HPS lamps or LEDs with varying proportions of red (R) and blue (B) light from 0600 to 2000 HR. *Celosia*, *Petunia*, *Impatiens*, *Tagetes*, and *Viola* were placed under treatments on 29 March and 24 May 2012 and *Antirrhinum*, *Catharanthus*, *Pelargonium*, and *Salvia* were placed under treatments on 18 Sept. and 23 Oct 2012.

Treatment initiation	Supplemental light source	Supplemental light ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Solar DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Plant temperature (ºC)
29 Mar.	HPS	102.4 ± 6.8	7.1 ± 2.1	19.5 ± 2.6
	100R:0B	98.4 ± 1.2	8.4 ± 3.3	18.2 ± 3.1
	85R:15B	99.9 ± 2.2	7.7 ± 1.5	18.4 ± 3.2
	70R:30B	99.2 ± 3.1	5.2 ± 1.2	17.7 ± 2.5
24 May	HPS	97.6 ± 3.2	6.8 ± 2.0	22.2 ± 3.5
	100R:0B	101.5 ± 3.6	5.1 ± 1.5	21.0 ± 2.7
	85R:15B	98.7 ± 3.6	5.6 ± 1.5	21.0 ± 4.0
	70R:30B	98.4 ± 5.7	5.6 ± 1.6	20.7 ± 3.1
18 Sep.	HPS	97.8 ± 3.6	2.6 ± 1.1	19.8 ± 2.8
	100R:0B	97.2 ± 2.1	3.4 ± 1.8	18.3 ± 1.9
	85R:15B	99.2 ± 2.9	2.8 ± 1.2	18.0 ± 2.1
	70R:30B	93.8 ± 2.4	3.0 ± 1.7	18.4 ± 2.4
23 Oct.	HPS	93.1 ± 3.3	2.7 ± 1.9	20.7 ± 2.4
	100R:0B	98.6 ± 3.9	2.4 ± 1.5	18.6 ± 1.9
	85R:15B	101.4 ± 1.8	2.4 ± 1.8	19.0 ± 2.1
	70R:30B	97.6 ± 2.7	2.1 ± 1.0	18.4 ± 2.4

Supplemental lighting treatments.

Seedlings were grown under ambient solar light supplemented with 100 μmol·m^{-2}·s^{-1} *PPF* at plant height [as measured with a spectroradiometer (PS-100; Apogee Instruments, Logan, UT)] from 0600 to 2200 HR (Table 1) which provided a supplemental DLI of 5.8 mol·m^{-2}·d^{-1}. Supplemental light was delivered from a 150-W HPS lamp (PL2000; P.L. Lights, Beamsville, Ontario, Canada) or one of three LED arrays (Philips GreenPower LED research module; Koninklijke Philips Electronics N.V., Netherlands). Each LED arrays were spaced on 6.3-cm centers and consisted of 48.5 cm-long and 3.3 cm-wide square aluminum bars containing five 660- or 470-nm LEDs. The 100:0, 85:15, and 70:30 red:blue ratio treatments contained 20 red bars, 18 red and 4 blue bars, and 15 red and 7 blue bars alternating, respectively. Spectral scans of SL were taken at night at the beginning and end of each replication with a spectroradiometer (PS-100; Apogee Instruments, Inc.). Spectral quality of SL sources is shown in Figure 1. Electrical use (kWh·d^{-1}) for both HPS lamps and LED lights were measured using an electrical meter (P440 Kill A Watt; P3 International, New York, NY).

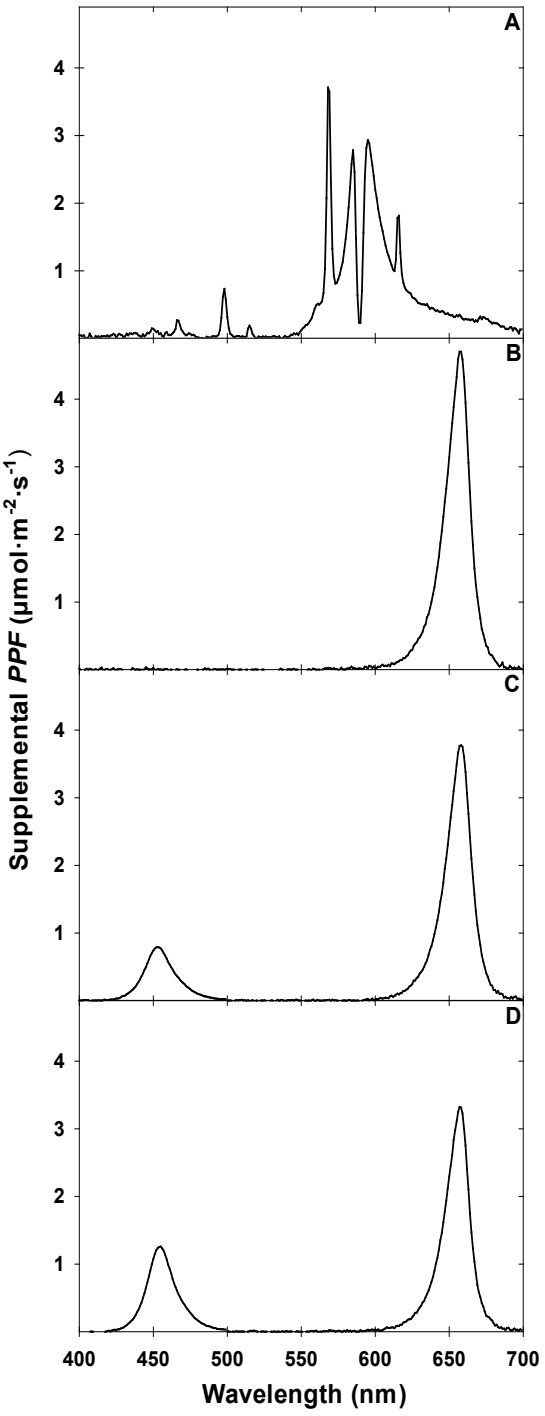

Figure 2.1 (A−D) Spectral quality of 100 µmol·m^{-2}·s^{-1} delivered from high pressure sodium (HPS) lamps (A) or light-emitting diodes (LEDs) with (%) 100:0 (B), 85:15 (C), 70:30 (D) red:blue light.

Finishing culture and environment.

Twenty-eight days after the placement of trays under SL sources, 10 randomly selected seedlings from each tray were transplanted into 10.2-cm (460-mL) containers (Dillen Products, Middlefield, OH) filled with a soilless medium comprised of (by vol.) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2; Fafard, Inc., Agawam, MA). Plants were placed in a common finish environment with a 16-h photoperiod of ambient light supplemented with a *PPF* of 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from HPS lamps to provide a target DLI of ≈10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$. Air temperatures in the finishing environment were 22.7 ± 2.2 and 22.1 ± 3.2 °C (group I) and 21.1 ± 0.6 and 21.9 ± 1.8 °C (group II). Plants were irrigated as necessary with acidified water supplemented with a combination of two water-soluble fertilizers (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris, Marysville, OH) to provide the following ($mg \cdot L^{-1}$): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo.

Data collection and calculations.

At 14, 21, and 28 d after initiating SL treatments, 25 plants of each species were randomly harvested and measured for pullability (the number of seedlings that can be pulled from the tray with roots and media intact). The collective roots and shoots of the 25 plants were washed and placed in a drying oven at 70 °C. After 4 d, roots and shoots were weighed to determine collective root dry mass (RDM) and shoot dry mass (SDM), respectively.

At 28 d after initiating SL treatments, 10 plants from each species were randomly selected and measured for stem length (measured from the base of the hypocotyl to the shoot apical meristem) and stem caliper above the lowest leaf with a digital caliper

(digiMax; Wiha, Schonach, Germany). Relative chlorophyll content was measured with a SPAD meter (SPAD-502; Konica Minolta Sensing, INC., Osaka, Japan). After nondestructive measurements were recorded, roots and shoots of all selected seedlings were washed and separated, placed in a drying oven at 70 °C for at least 4 d, and RDM and SDM were recorded. The sturdiness quotient (SQ) was calculated as stem caliper divided by stem length. The quality index (QI), an objective, integrated, and quantitative measurement of quality, was calculated as the [total dry mass × (shoot:root ratio + sturdiness quotient)] (Currey et al., 2013).

Transplants in the finish environment were monitored daily following planting. When the first flower opened, the date, node number beneath the first open flower, and plant height from the surface of the medium to the top of the plant were recorded. Time to flower was calculated as the time from transplant into the finish environment to the first flower opening.

Statistical analysis.

The experiment used a complete block design, replicated twice in time for each of the nine species. There were ten samples (individual plants) per species per SL treatment for seedling and finish data. Data were analyzed using SAS (SAS 9.3; SAS Institute Inc., Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance.

Results

Height.

Height of all species with the exception of *Pelargonium* was significantly shorter under LED SL treatments (Fig. 2 A−C). For example, height of *Catharanthus*, *Celosia*, *Impatiens*, *Petunia*, *Salvia*, *Tagetes*, and *Viola* was 31, 29, 31, 55, 20, 9, and 35% shorter

for seedlings grown under the 85:15 red:blue LEDs compared to those grown under HPS lamps, respectively. *Antirrhinum* seedlings under 70:30 red:blue LEDs were 9% shorter than those grown under HPS lamps.

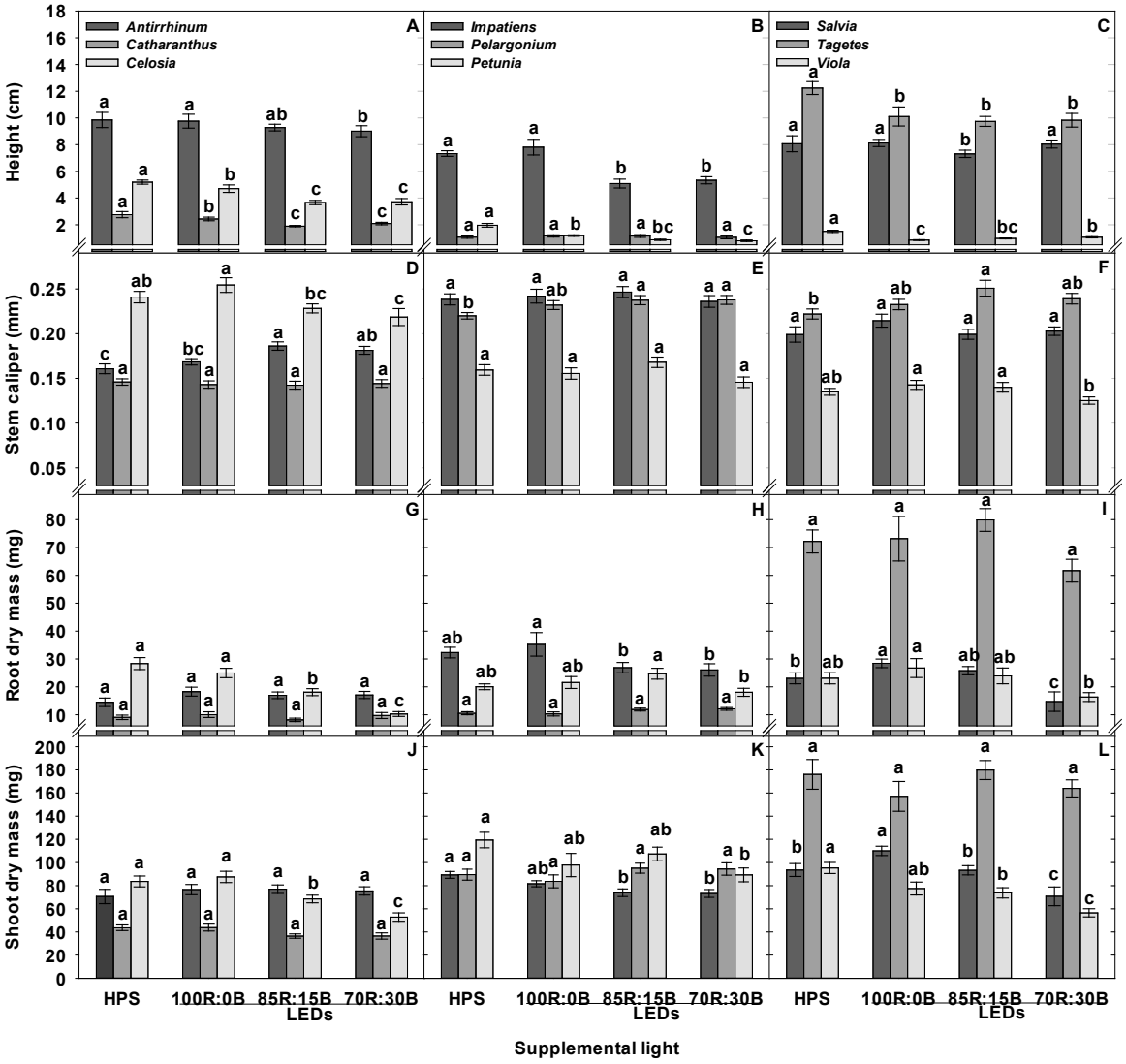

Figure 2.2 (A–L) Effect of 100 µmol·m^{-2}·s^{-1} of supplemental light delivered from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) with varying proportions of red:blue light during seedling production on height, stem caliper, root dry mass, and shoot dry mass for *Antirrhinum*, *Catharanthus*, *Celosia*, *Impatiens*, *Pelargonium*, *Petunia*, *Salvia*, *Tagetes*, *and Viola* after 28 d. Different lower-case letters across supplemental light source within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Stem caliper.

Stem caliper of *Antirrhinum*, *Pelargonium*, and *Tagetes* seedlings was significantly larger under LED treatments (Fig. 2D−F). For example, stem caliper of *Antirrhinum*, *Pelargonium*, and *Tagetes* was 16, 8, and 13% larger, respectively, for seedlings grown under the 85:15 red:blue LEDs compared to seedlings grown under HPS lamps. Under 70:30 red:blue LEDs, stem caliper of *Celosia* and *Viola* seedlings was significantly smaller than under the other SL treatments. Stem caliper of *Celosia* grown under 70:30 red:blue LEDs was 9% smaller than plants grown under HPS lamps. Stem caliper of *Catharanthus*, *Impatiens*, *Petunia*, and *Salvia* was not significantly influenced by SL treatments.

Root dry mass.

Root dry mass of *Celosia* and *Impatiens* was highest under the HPS lamps and 100:0 red:blue LEDs (Fig. 2 G−I). However, RDM of *Petunia*, *Salvia*, and *Viola* was lowest under the 70:30 red:blue LEDs. For example, RDM of *Salvia* was 36% lower for plants grown under 70:30 red:blue LEDs than under HPS lamps. There were no significant differences in RDM between HPS and LED SL treatments for *Antirrhinum*, *Catharanthus*, *Pelargonium*, and *Tagetes*.

Shoot dry mass.

Shoot dry mass of *Celosia* was highest under the HPS and 100:0 red:blue LEDs (Fig. 2J−L). The SDM of *Impatiens*, *Petunia*, *Salvia*, and *Viola* was lowest under the 70:30 red:blue LEDs. For example, SDM of *Impatiens*, *Petunia*, *Salvia*, and *Viola* was 18, 25, 24, and 40% lower under 70:30 red:blue LEDs, respectively, than under HPS lamps.

However, there were no significant differences in SDM of *Antirrhinum*, *Catharanthus*, *Pelargonium*, and *Tagetes* between HPS and LED SL treatments.

Sturdiness quotient.

Sturdiness quotient of *Antirrhinum*, *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, *Tagetes*, and *Viola* was highest under LED SL treatments (Fig. 3A−C). For example, SQ of *Antirrhinum* and *Pelargonium* was 22 and 23% higher under the 70:30 red:blue LEDs when compared to HPS lamps. Sturdiness quotient of *Impatiens* was 54% higher under 85:15 red:blue LEDs, than plants grown under HPS lamps. For *Celosia* and *Salvia*, SQ was not significantly different between HPS and LED SL treatments.

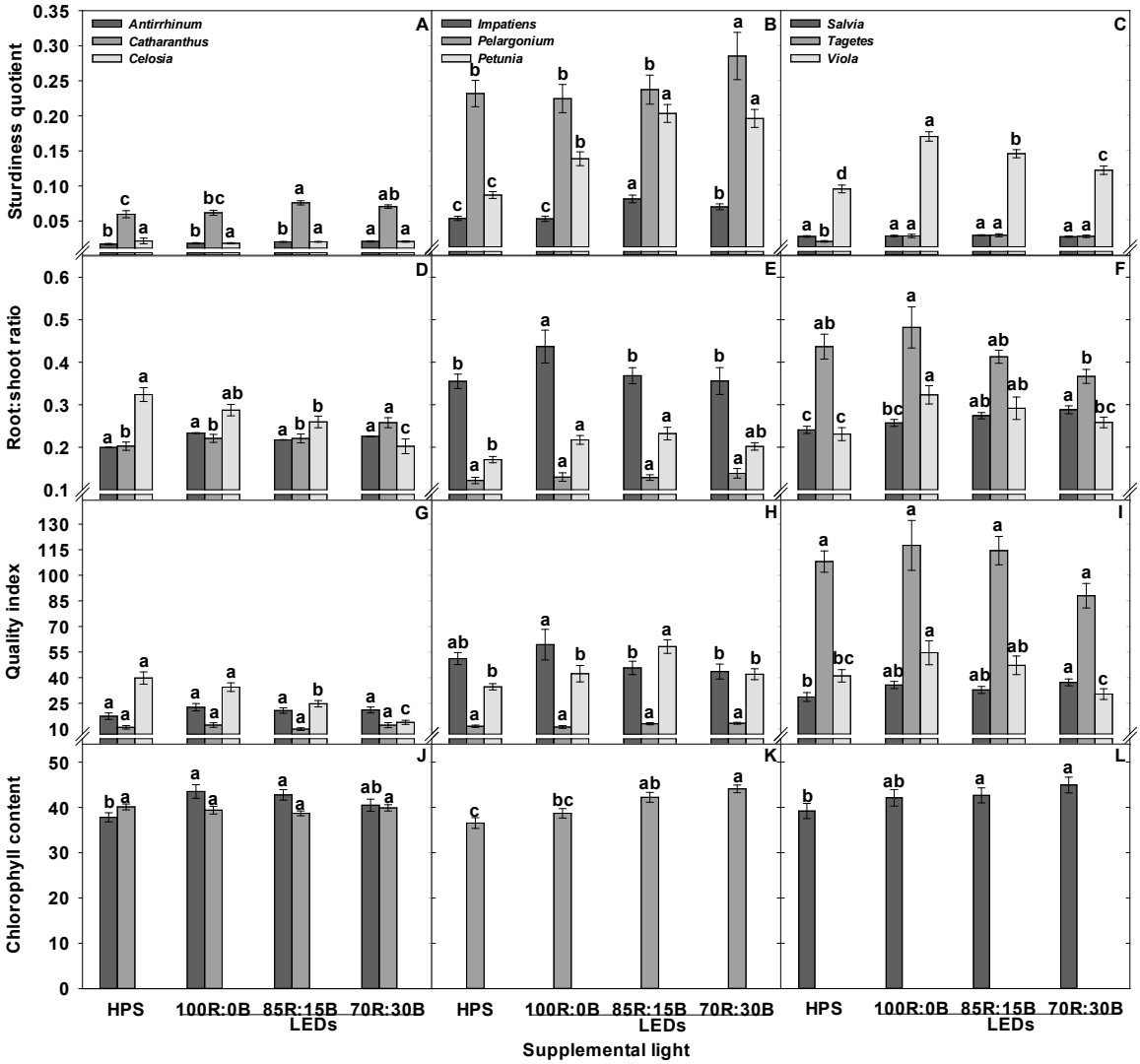

Figure 2.3(A–L) Effect of 100 µmol·m^{-2}·s^{-1} of supplemental light delivered from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) with varying proportions of red:blue light during seedling production on sturdiness quotient, root:shoot ratio, quality index, and chlorophyll content for *Antirrhinum, Catharanthus*, *Celosia*, *Impatiens*, *Pelargonium*, *Petunia*, *Salvia*, *Tagetes*, and *Viola* on 28 d. Different lower-case letters across supplemental light source within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Root:shoot ratio.

Root:shoot ratio was highest under LED SL treatments for *Catharanthus*, *Impatiens*, *Petunia*, *Salvia*, and *Viola* (Fig. 3 D−F). For example, root:shoot ratio of *Catharanthus* and *Impatiens* was 27 and 23% higher under the 70:30 red:blue LEDs and 100:0 red:blue LEDs, respectively, than under HPS lamps. However, root:shoot ratio was lowest under the 70:30 red:blue LEDs for *Celosia* and *Tagetes*. No significant differences between HPS and LED SL treatments were found for root:shoot ratio of *Antirrhinum* and *Pelargonium*.

Quality index.

Under LED SL treatments, QI of *Petunia*, *Salvia*, and *Viola* was highest compared to HPS lamps (Fig. 3 G−I). For example, QI of *Petunia*, *Salvia*, and *Viola* was 68, 30, and 33% higher under 85:15, 70:30, and 100:0 red:blue LEDs, respectively, than under HPS lamps. Quality index of *Celosia* was highest under the HPS lamps. Quality index was not significantly influenced by SL treatment for *Antirrhinum*, *Catharanthus*, *Impatiens*, *Pelargonium,* and *Tagetes*.

Relative chlorophyll content.

Relative chlorophyll content was highest under LED SL treatments for *Antirrhinum*, *Pelargonium*, and *Salvia* (Fig. 3 J−L). For example, relative chlorophyll content was 21 and 15% higher, respectively, for *Pelargonium* and *Salvia* seedlings grown under 70:30 red:blue LEDs than under HPS lamps. However, relative chlorophyll content of *Catharanthus* was not significantly different under HPS or LED SL treatments.

Height at flower.

Catharanthus and *Pelargonium* were shorter at flower when grown under HPS lamps compared to LED SL treatments (Fig. 4 A−C). For example, *Pelargonium* was 42% shorter at the time of flower when grown under HPS lamps compared to 100:0 red:blue LEDs. However, height at the time of first open flower was not significantly different for *Antirrhinum*, *Celosia*, *Impatiens*, *Petunia*, *Salvia*, *Tagetes*, or *Viola* grown under HPS or LED SL treatments.

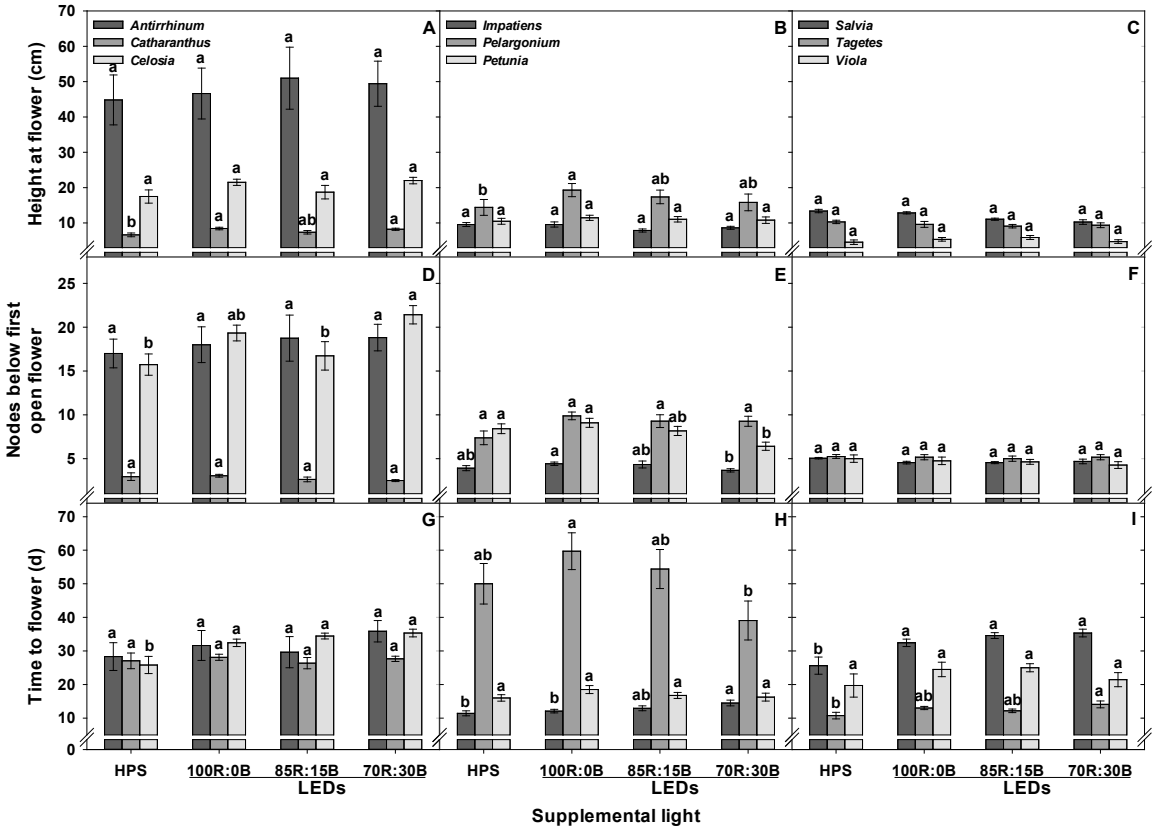

Figure 2.4. (A–I) Effect of 100 µmol·m^{-2}·s^{-1} of supplemental light delivered from high-pressure sodium (HPS) lamps or light-emitting diodes (LEDs) with varying proportions of red:blue light during seedling production on finish height, number of nodes below the flower, and time to flower for *Antirrhinum, Catharanthus*, *Celosia*, *Impatiens*, *Pelargonium*, *Petunia*, *Salvia*, *Tagetes*, and *Viola*. Different lower-case letters across supplemental light source within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Nodes below open flower.

Celosia had more nodes below the first open flower when grown under 70:30 red:blue LEDs compared to other SL treatments; however, *Impatiens* and *Petunia* had fewer nodes below the first open flower when grown under 70:30 red:blue LEDs compared to other SL treatments (Fig. 4 D−F). *Petunia*, for example, had two fewer nodes below the first open flower for plants grown under 70:30 red:blue LEDs compared to HPS lamps. No significant difference in the number of nodes below the first open

flower was observed for *Antirrhinum*, *Catharanthus*, *Pelargonium*, *Salvia*, *Tagetes*, and *Viola* grown under HPS or LED SL treatments.

Time to flower.

Time to flower for *Pelargonium*, occurred 20 d earlier for plants grown under 70:30 red:blue LEDs compared to plants grown under 100:0 red:blue LEDs (Fig. 4 G−I). Time to flower of *Celosia*, *Impatiens*, *Salvia*, and *Tagetes* was generally slower for plants grown under LEDs compared to HPS lamps. However, TTF was not significantly different for plants grown under HPS or LED SL treatments for *Antirrhinum*, *Catharanthus*, *Petunia*, and *Viola*.

Discussion

A high-quality seedling is one that is compact, fully rooted with a large stem caliper and high RDM. Compact seedlings with a large stem caliper and RDM are less likely to be damaged during shipping and transplant (Pramuk and Runkle, 2005b). The QI is a useful tool to assess young plant quality by integrating the above morphological parameters that contribute to the perceived quality of plugs and liners (Currey et al., 2013). In our study, parameters of seedling quality using the QI were similar to HPS lamps or higher for *Antirrhinum*, *Catharanthus*, *Impatiens*, *Petunia*, *Pelargonium*, *Salvia*, *Tagetes*, and *Viola* grown under LED SL for 28 d. *Celosia* was the only species where the QI was lowest under LED treatments providing blue light.

Antirrhinum, *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* grown under the 85:15 and 70:30 red:blue LEDs were generally more compact with a larger stem caliper, higher SQ, and higher relative chlorophyll content than plants grown under HPS lamps. The RDM of these species was statistically similar to those produced under

HPS lamps. However, SDM of *Impatiens* and *Petunia* was lower when seedlings were grown under LEDs containing blue light. Several studies have highlighted the importance of blue light when used as sole-source or SL. For example, number of tillers in *Triticum aestivum* L. 'USU-Super Dwarf' (wheat) was similar under 90:10 red:blue light as plants grown under white light. Additionally, 15 d after transplant, SDM increased from 0.85 to 1.42 g and photosynthesis increased from 5.3 to 8.3 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ as the proportion of blue light supplementing red light increased from 1 to 10% (Goins et al., 1997). Dueck et al. (2012) demonstrated that leaf thickness of 'Sunstream' tomato plants increased by 12% when grown under LEDs with a ratio of 88:12 red:blue light compared to those grown under HPS lamps. When *Arabidopsis thaliana* L. plants were grown under 100:0 red:blue LEDs, they exhibited abnormal leaf morphology, delayed flowering, and reduced seed production. However, 90:10 red:blue fluorescent light resulted in plants that had a similar TTF and increased germination rate compared to plants grown under white fluorescent light (Goins et al., 1998). When cuttings of *Impatiens hawkeri* W. Bull 'Celebrette Frost' and *Pelargonium ×hortorum* L.H. Bailey 'Designer Bright Red' were grown under SL from HPS lamps, 100:0, 85:15, or 70:30 red:blue LEDs, no significant differences in growth and morphology were observed. However, leaf dry mass, root dry mass, root mass ratio, and root:shoot ratio increased 15, 36, 17, and 24%, respectively for petunia 'Suncatcher Midnight Blue' cuttings grown under 70:30 red:blue LEDs compared to HPS lamps (Currey and Lopez, 2013).

Our results show that relative chlorophyll content increased as the amount of blue light increased for some species. XiaoYing et al. (2011) focused on the cellular changes that result from using different color wavelength LEDs on tomato. Plants grown under

any LED treatment with blue light had significantly thicker leaves and longer palisade cells than plants grown in other LED treatments. For example, leaf thickness and palisade cell length were 23.1 and 2.5 µm under 100:0 red:blue LEDs, but increased to 35.9 and 14.4 µm under 50:50 red:blue LEDs, a 55.4 and 476.0% increase, respectively. Additionally, chloroplasts were more developed and stomata density increased under the red:blue LEDs compared to the monochromatic red LEDs. Additionally, enhanced net photosynthesis was measured for leaves irradiated with blue LEDs. Similarly, our study demonstrated that relative chlorophyll content increased by 21 and 15% for *Pelargonium* and *Salvia* grown under 70:30 red:blue LEDs compared to HPS lamps, respectively.

Time to flower of *Celosia*, *Impatiens*, *Salvia*, and *Tagetes* was reduced for plants grown under the HPS lamps compared to most of the LED treatments. We postulate that hastened flowering could be attributed to increased seedling temperature of ≈1 to 2 °C under HPS lamps (Table 1). High-pressure sodium lamps are rated to be 25 to 30% efficient at converting electrical energy to light; the other 70 to 75% is radiated as heat energy (Spaargaren, 2001). *Celosia* is the only species considered cold-sensitive and must be grown under higher temperatures as it has an estimated base temperature of 10 °C (Runkle and Blanchard, 2011). Pramuk and Runkle (2005a) demonstrated the influence of temperature and use of SL from HPS lamps on development of *Celosia*. Time to flower was quadratically related to DLI and temperature; as temperature increased up to ≈25 °C and DLI increased from 5 to 15 $mol \cdot m^{-2} \cdot d^{-1}$, TTF decreased. However, further increase in DLI had no significant effect on TTF. Additionally, as temperature increased from 15 to 28 ºC under an average DLI of 8 $mol \cdot m^{-2} \cdot d^{-1}$, plant height increased from 17 to 27 cm (37%). When HPS lamps were used to increase the

DLI from 5 to 25 mol·m^{-2}·d^{-1}, shoot dry mass doubled from 3.6 to 7.2 g for plants grown under 25 °C.

Previous studies with bedding plants have demonstrated that increased DLI during the young plant stage results in earlier flowering during the finish stage (Hutchinson et al, 2012; Lopez and Runkle, 2008; Oh et al., 2010). For example, increasing DLI with SL later in the plug stage for petunia 'Madness Red' and pansy 'Delta Premium Yellow' resulted in earlier flowering, but lower dry mass and bud number than in the first one or two-thirds of production. Supplemental lighting during the entire plug stage and last two-thirds of plug stage reduced time to flower by 4.8 and 4.7 d in petunia and 4.7 and 5.7 d in pansy, respectively, when compared to the photoperiodic low light control (Oh et al., 2010). Similarly, as DLI increased from 1.2 to 12.3 mol·m^{-2}·d^{-1}, TTF decreased by 23 and 19 d for *Angelonia angustifolia* 'AngelMist White Cloud' and *Osteospermum ecklonis* 'Voltage Yellow', respectively (Hutchinson et al., 2012). Although we did not have a treatment without supplemental lighting, we provided the same DLI with all our SL treatments and determined that TTF was similar for *Antirrhinum*, *Catharanthus*, *Petunia*, and *Viola* grown under the HPS lamps and LEDs.

Although energy consumption and efficiency of SL sources were not a primary focus of this study, they do warrant mentioning. The daily energy consumption for the HPS, 100:0, 85:15, and 70:30 red:blue was as follows: 3.01, 1.23, 1.35, 1.56 kWh·d^{-1}, respectively. Energy consumption from the LEDs to light five plugs trays decreased by 59.1, 55.1, and 48.2% for the 100:0, 85:15, and 70:30 red:blue LED arrays, respectively, compared to one 150 W HPS lamp. The LED arrays used in this study were passively cooled; and therefore, did not use any additional energy for active cooling as compared to

the LEDs used by Currey and Lopez (2013). As a result of using passively cooled LEDs, ambient solar radiation was blocked by approximately 50% due to the increased size of the fixtures. Currey and Lopez (2013) found that using actively cooled LEDs with forced-air cooling consumed 3.29, 3.43, and 4.06 $kWh \cdot d^{-1}$ for 100:0, 85:15, and 70:30 red:blue LEDs, respectively, compared to HPS lamps that used 3.01 $kWh \cdot d^{-1}$. They calculated the energy consumption of the fans used to cool the arrays and reported that they accounted for 37 to 45% of the energy consumed by the LED arrays. Without fans, the LED arrays showed a 15 to 40% energy reduction compared to the HPS lamps. The need for heat dissipation without significant shading poses challenges to developing LED arrays for greenhouse use, because the materials used to construct LED arrays are important factors for thermal dissipation (Bourget, 2008; Christensen et al., 2009).

The QI of the majority of species tested in this study were similar or higher for plants grown under SL from LEDs containing both red and blue light compared to those seedlings grown under HPS lamps. For species where TTF was delayed when seedlings were grown under LEDs, the delay was not commercially significant with the exception of *Celosia* and *Salvia*. Therefore, a light ratio of 85:15 red:blue light could be a good combination for greenhouse LED SL of bedding plant plugs. However, it is also important to remember that although blue LEDs have a higher electrical conversion efficiency compared to red LEDs, blue light is a higher-energy light, which increases energy consumption as higher proportions of blue are used. Therefore, further research is necessary to determine if lower amounts of blue light can yield adequate plant responses. Our results indicate that providing SL from LEDs or HPS lamps has a positive influence

on seedling RDM, height, and stem caliper leading to high-quality bedding plant seedlings when solar light is limiting.

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END-OF-DAY MANIPULATION OF PHYTOCHROME AND CRYPTOCHROME USING LIGHT-EMITTING DIODES INFLUENCES SEEDLING STEM LENGTH AND MORPHOLOGY OF SOME BEDDING PLANT SPECIES

Introduction

Annual bedding plant sales were the highest grossing sector of the U.S. commercial floriculture industry, accounting for nearly $3.6 billion in 2012 (USDA, 2014), and are produced from either vegetative cuttings or seeds (Klopmeyer et al., 2003; Styer, 2003). Seed propagated bedding plants are produced in two distinct phases: a young plant stage, in which seedlings are propagated in plug trays, and a finish plant stage in which the rooted young plants are transplanted into a larger finish container where they are grown to marketability (Hamrick, 2003). Seedlings or plugs are considered high-quality when they are compact, fully-rooted transplants with a large stem caliper and high root dry mass, and flower rapidly after transplant (Latimer, 1998). Seedlings with elongated stems or under-developed roots are considered poor quality, weak, and subject to environmental stress during shipping (Johkan et al., 2010; Pramuk and Runkle, 2005; Seiler and Johnson, 1988). Therefore, controlling stem elongation during plug production is crucial to maintain quality, and several methods can be used to control stem elongation. For example, cold water irrigation, chemical plant growth regulators (PGRs), mechanical stimulation, reduced fertilization, photoselective films, and a negative difference between day and night

temperature (day temp. – night temp. = DIF) have all been shown to reduce stem length in greenhouse crops, but each technique has limitations, especially in a commercial setting (Barrett and Erwin, 1994; Kuehny et al., 2001; Latimer, 1998; Nelson, 1994; Runkle and Heins, 2003; Shimizu and Heins, 2000). Plugs are generally produced in 288-cell (6 mL) or 512-cell (3.1 mL) plug trays that promote stem elongation due to the shade avoidance response and dense planting conditions (Armitage and Kaczperski, 1994; Styer, 2003).

Red and far-red (FR) light during twilight or at the end of the photoperiod using end-of-day (EOD) lighting treatments, is known to influence stem length (Blom et al., 1995; Chia and Kubota, 2010; Decoteau et al., 1988; Kasperbauer and Peaslee, 1973). Many of the effects on plant growth and morphology from EOD lighting are caused by photoreversion, which is mediated by phytochrome (Decoteau and Friend, 1991). Phytochrome is a family of proteins in plants that have two forms, the R-light-absorbing form, $P_{r,}$ and the FR-light-absorbing form, P_{fr}. Far-red light is important for a number of photomorphogenic responses in plants. Phytochromes are responsible for R and FR light responses including germination, seedling de-etiolation, stem elongation, floral induction, and shade avoidance (Withrow et al. 1957; Mohr, 1964; Fankhauser, 2001; Franklin and Whitelam, 2005). When *Petunia* (*P.* ×*hybrida* Vilm.-Andr. 'Easy Wave White') and *Antirrhinum* (*Antirrhinum majus* L. 'Liberty Classic Cherry'), both long-day plants [LD (LDP)], were grown under a R:FR light ratio that ranged from 0.66 to 2.38 and 0.28 to 1.07, respectively, flowering was promoted. However, when *Tagetes* (*T. erecta* L. 'American Antigua Yellow'), a short-day plant [SD (SDP)], was grown with a R:FR light ratio ≥0.66, flowering was delayed (Craig and Runkle, 2012). A separate study

investigated movable and stationary FR LEDs to promote hypocotyl elongation of *Cucurbita* (*Cucurbita maxima* ×*C. moschata* Duchesne 'Tetsuxabato') for grafting. Hypocotyls were 55% and 69% longer, respectively, for plants grown under movable or stationary FR LEDs compared to plants grown without FR light (Yang et al., 2012).

Blue (B) light also plays a number of key photomorphogenic roles in plants; including stomatal control, stem elongation, and phototropism (Blaauw and Blaauw-Jansen, 1970; Massa et al., 2008). Blue light-mediated cryptochromes are a class of receptors known as cry receptors, where both cry1 and cry2 receptors strongly inhibit stem elongation, contribute to leaf expansion, and the cry2 receptor is required for a timely transition to the reproductive state (Folta and Childers, 2008; Guo et al., 1999; Valverde et al., 2004). Blue light has been shown to be involved in flower induction in some LDP (Bagnall et al., 1996; Runkle and Heins, 2001). Additionally, Folta and Spalding (2001) demonstrated that an inhibition of hypocotyl elongation can be elicited in as few as 30 seconds after seedlings are irradiated with B light. Another study showed that *Chrysanthemum* (*Chrysanthemum* ×*grandiflorum* Ramat. 'Ragan') internode elongation was reduced by up to 60% when plants were treated with a 4-h night break of B LED light compared to the fluorescent control (Shimizu et al., 2006).

EOD lighting has been effectively used to promote or repress stem elongation in some vegetable and ornamental crops. For example, Decoteau and Friend (1991) showed that EOD lighting high in R light (high R:FR) can be used to generate short, compact *Citrulls* [*Citrulls lanatus* (Thunb.) Matsum & Naki 'Sugar Baby'] transplants. For instance, stem length of plants treated with 15 min of R light was reduced by 30% compared to those treated with 15 min of FR at the end of a 12-h photoperiod. In a

separate study, *Chrysanthemum* (*C.* ×*morifolium* Ramat. 'Coral Charm') was grown under LEDs providing 30 min EOD lighting with R:FR ranging from 0.4 to 2.4. Stem length decreased by ≈8 mm as the EOD R:FR increased from 0.4 to 2.4 (Lund et al., 2007). Chia and Kubota (2010) found that EOD treatments high in FR light (low R:FR) can be used to promote hypocotyl elongation of commercial *Solanum* rootstock cultivars (*S. lycopersicum* L. 'Aloha' and *S. lycopersicum* L. × *S. habrochaites* Knapp and Spoone 'Maxifort'). Although these results suggest a high R:FR would be most suitable for EOD lighting to achieve compact bedding plant seedlings, previous studies indicate stem elongation in response to light quality can be variable and species dependent (Runkle and Heins, 2001).

To our knowledge, no previous studies have quantified the effect of EOD lighting during seedling propagation on stem elongation, morphology, and subsequent flowering of day neutral, LD, and SD annual bedding plants. Our objectives were to 1) quantify stem elongation and morphological characteristics of bedding plant seedlings, and subsequent time to flower of seedlings grown under EOD LED lighting of low, medium, and high R:FR, 2) compare EOD LED to EOD incandescent (INC) and compact fluorescent lamp (CFL) lighting, and 3) determine which proportion of R:B:FR minimizes stem elongation without negatively influencing subsequent flowering.

Materials and Methods

Expt. 1. End-of-day red and far-red lighting.

Seeds of *Cosmos*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* (Ball Horticulture, West Chicago, IL) were sown into 288-cell (6 mL) plug trays at a commercial greenhouse (Heartland Growers, Westfield, IN). Upon hypocotyl emergence,

plants were delivered to Purdue University in West Lafayette, IN (lat. 40° N) on 10 Jan. (season I), 06 March (season II), and 01 May, 2012 (season III) to begin treatments (day 0). Plant material was maintained in a glass-glazed greenhouse with exhaust fan and evaporative-pad cooling, radiant hot water heating, and retractable shade curtains controlled by an environmental control system (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada).

One plug tray of each species was placed in each of six greenhouse automated blackout chambers (VRE Sytems, Grassie, Ontario, Canada). Blackout cloth was opened at 0800 HR and retracted over each chamber at 1630 HR. The photoperiod consisted of an 8.5-h natural day (0800 to 1630 HR) with supplemental light from HPS lamps that provided a supplemental *PPF* of ≈50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at canopy level (HID; PARsource, Petaluma, CA) in each chamber. End-of-day light treatments were delivered daily by one of five light treatments providing 30 min (1630 to 1700 HR) of light for 21 d and a no EOD control. The EOD treatments included 100 W INC lamps (reveal 100; GE, Cleveland, OH) providing R:FR ≈0.78, 100 W CFLs (Ecosmart Home Depot, Atlanta, GA) providing a R:FR ≈8.4, and 122-cm long by 0.64-cm wide low-intensity R and FR light emitting diode arrays (LED bars; ORBITEC, Madison, WI). Each LED treatment delivered a photon flux of 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from either (%) 100:0 (R:FR ≈212), 75:25 (R:FR ≈4.5), or 50:50 (R:FR ≈0.9) R:FR LEDs. The R, FR, total photon flux, and phytochrome photostationary state (PSS, calculated according to Sager et al., 1988) for the EOD light treatments are provided in Table 1.

The average daily air temperatures (ADT) and daily light integrals (DLI) for seasons I, II and III were 21.9 ± 1.1, 21.5 ± 0.9, and 22.8 ± 1.7 ºC; and 4.8 ± 1.3, 4.8 ± 1.1, and 5.1 ± 1.9 mol·m^{-2}·d^{-1}, respectively.

Expt. II. End-of-day red, blue, and far-red lighting.

Seeds of *Capsicum*, *Petunia*, *Solanum*, and *Tagetes* (Ball Horticulture) were sown as previously described and placed under EOD treatments on 28 Nov., 2012 (season I) and 16 Jan., 2013 (season II).

The photoperiod consisted of a 9.0-h natural day (0800 to 1700 HR) with supplemental light of ≈50 µmol·m^{-2}·s^{-1} from HPS lamps (PARsource). End-of-day lighting was delivered by one of five light treatments providing 30 min (1700 to 1730 HR) of light and a no-EOD control using the same automated black cloth system described in Expt. 1. Each light treatment delivered a total photon flux of 20 µmol·m^{-2}·s^{-1} from either (%) 100:0:0, 0:100:0, 75:25:0, 25:75:0, or 62:33:5 R:B:FR LED lights as described in Expt. 1.

The ADTs and DLIs for season I and II were 21.4 ± 0.6 and 21.0 ± 1.8 °C and 4.7 ± 0.8 and 4.4 ± 1.0 mol·m^{-2}·d^{-1}, respectively.

Table 3.1 The red (R), blue (B), far-red (FR), and total photon flux of light-emitting diodes (LEDs), incandescent (INC) lamps and compact fluorescent lamps (CFL), R:FR ratio and phytochrome photostationary state (PSS) describing the end-of-day (EOD) light quality obtained from measurements averaged over repeated experiments

	Photon flux ($\mu mol \cdot m^{-2} \cdot s^{-1}$)					
Treatment	Total[z]	R[y]	B[x]	FR[w]	R:FR	PSS[v]
			Experiment I			
LEDs R:FR 100:0	20.6 ± 2.6	19.8 ± 2.3	--[u]	0.16 ± 0.2	212 ± 2.6[v]	0.89 ± 0.01
LEDs R:FR 75:25	21.4 ± 3.1	16.6 ± 3.0	--	4.6 ± 0.6	4.5 ± 0.8	0.82 ± 0.02
LEDs R:FR 50:50	18.7 ± 3.1	9.1 ± 3.6	--	9.3 ± 1.3	0.9 ± 0.2	0.71 ± 0.06
INC	8.9 ± 2.5	3.1 ± 1.0	--	3.8 ± 1.8	0.8 ± 0.02	0.73 ± 0.05
CFL	5.6 ± 2.1	2.1 ± 0.8	--	1.1 ± 1.7	8.4 ± 1.9	0.77 ± 0.08
			Experiment II			
LEDs R:B:FR 100:0:0	19.2 ± 5.7	19.2 ± 5.7	0.0	--	--	0.89 ± 0.01
LEDs R:B:FR 0:100:0	19.9 ± 4.1	0.0	19.9 ± 4.1	--	--	0.47 ± 0.06
LEDs R:B:FR 75:25:0	20.0 ± 6.0	14.4 ± 2.8	5.6 ± 4.8	--	--	0.88 ± 0.06
LEDs R:B:FR 25:75:0	21.4 ± 6.2	4.5 ± 1.4	16.7 ± 6.6	--	--	0.76 ± 0.04
LEDs R:B:FR 62:33:5	26.9 ± 10.1	16.8 ± 13.3	8.9 ± 3.7	1.2 ± 0.3	14.1 ± 2.0	0.85 ± 0.01

[z]Photon flux (λ = 350 to 800 nm).
[y]Photon flux of red light (λ = 600 to 700 nm).
[x]Photon flux of blue light (λ = 400 to 500 nm)
[w]Photon flux of far-red light (λ =700 to 800 nm).
[v]100 % R LEDs used in this treatment, which technically emit a very low FR photon flux of λ > 700 nm.
[u]B light was not used in Expt. 1.

Plug culture.

Plugs in Expt. 1 and 2 were irrigated with water-soluble fertilizer (Jack's LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) providing (in $mg \cdot L^{-1}$): 100 nitrogen (N), 10 phosphorus (P), 78 potassium (K), 18 calcium (Ca), 9.4 magnesium (Mg), 0.10 boron (B), 0.05 copper (Cu), 0.50 iron (Fe), 0.25 manganese (Mn), 0.05 molybdenum (Mo), and 0.25 zinc (Zn).

Expt. 1 and 2. Common environment during the finish stage.

On day 21, ten seedlings of each species were randomly selected from each tray (without use of border plants) and were transplanted into 10.2 cm (460 mL) containers (Dillen Products; Middleton, Ohio) filled with a soilless medium comprised of 70% peat and 30% perlite (Fafard Custom Mix, Conrad Fafard, Anderson, SC). Transplants were moved to a common finish environment with a 16-h photoperiod of ambient light supplemented with HPS lighting to provide an average ADT during Expt. 1 of 21.3 ± 0.9, 21.6 ± 1.4, and 21.4 ± 1.1 °C and a DLI of ≈ 12.6 ± 2.1, 12.8 ± 1.8, and 12.9 ± 2.6 $mol \cdot m^{-2} \cdot d^{-1}$ for seasons I, II, and III, respectively. The average ADT during Expt. 2 was 20.8 ± 2.1 and 20.9 ± 2.7 °C and the average DLI was 12.6 ± 2.9 and 11.4 ± 2.2 $mol \cdot m^{-2} \cdot d^{-1}$, respectively, for seasons I, and II. Plants were irrigated as necessary with acidified water supplemented with water-soluble fertilizer to provide (in $mg \cdot L^{-1}$): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo. Nutrients were supplied from a combination of two fertilizers, 900 $mg \cdot L^{-1}$ (Peters Excel© Cal-Mag 21N–2.2P–16.5K) and 300 $mg \cdot L^{-1}$ formulation (Peters Excel© 15N–2.2P–12.5K). Irrigation water was supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 $mg \cdot L^{-1}$ to reduce alkalinity to 100 $mg \cdot L^{-1}$ and pH to a range of 5.8 to 6.2.

Environmental data collection.

Spectral scans were taken of EOD treatments at night at the beginning and end of each season with a spectroradiometer [Fig. 1 and 2 (PS-100; Apogee Instruments, Inc., Logan, UT)]. Quantum sensors (LI-190, LI-COR Biosciences, Lincoln, NE) measured solar *PPF* at plant level every 30 s, and the average of each sensor was logged every 15 min by a data logger (Model CR1000; Campbell Scientific, Inc., Logan, UT). Resistance-based temperature sensors (External Temperature Sensor; Spectrum Technologies, Inc., Plainfield, IL), and enclosed thermocouples recorded temperature every 20 s and averages were logged every 15 min by a data logger [WatchDog Model 2000 (Plant Growth Stations; Spectrum Technologies, Inc., Plainfield, IL].

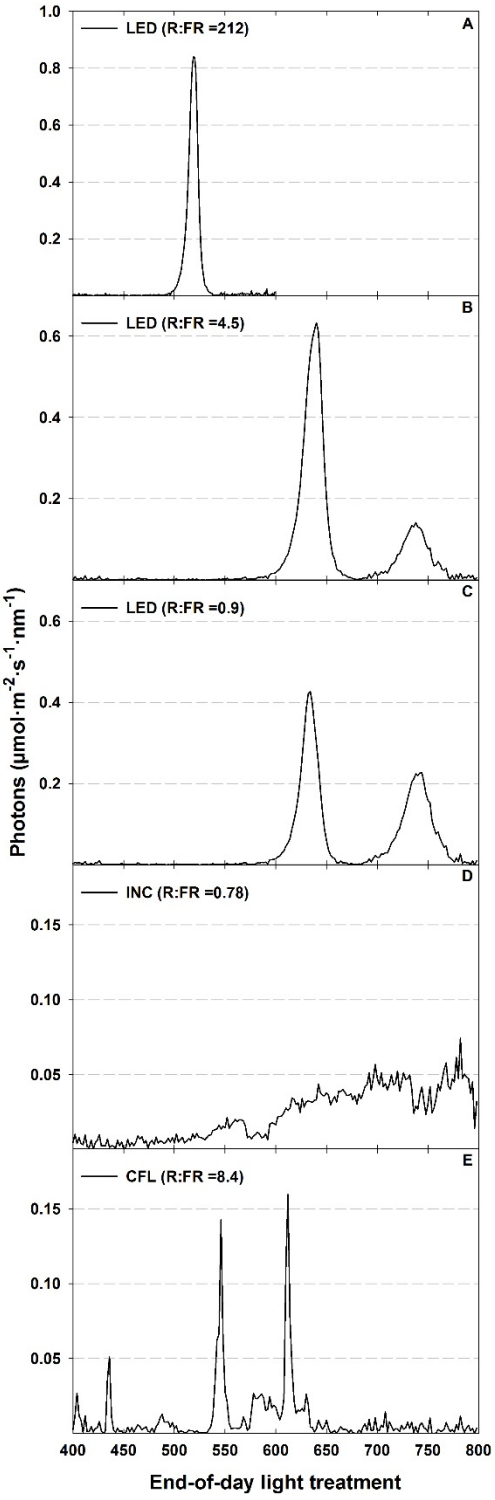

Figure 3.1. (A−E) Spectral quality of end-of-day light treatments from light-emitting diodes providing a red:far-red ratio (R:FR) ≈212, ≈4.5, or ≈0.9; incandescent lamps (INC) providing (R:FR) ≈0.78; or compact fluorescent lamps (CFL) providing (R:FR) ≈8.4.

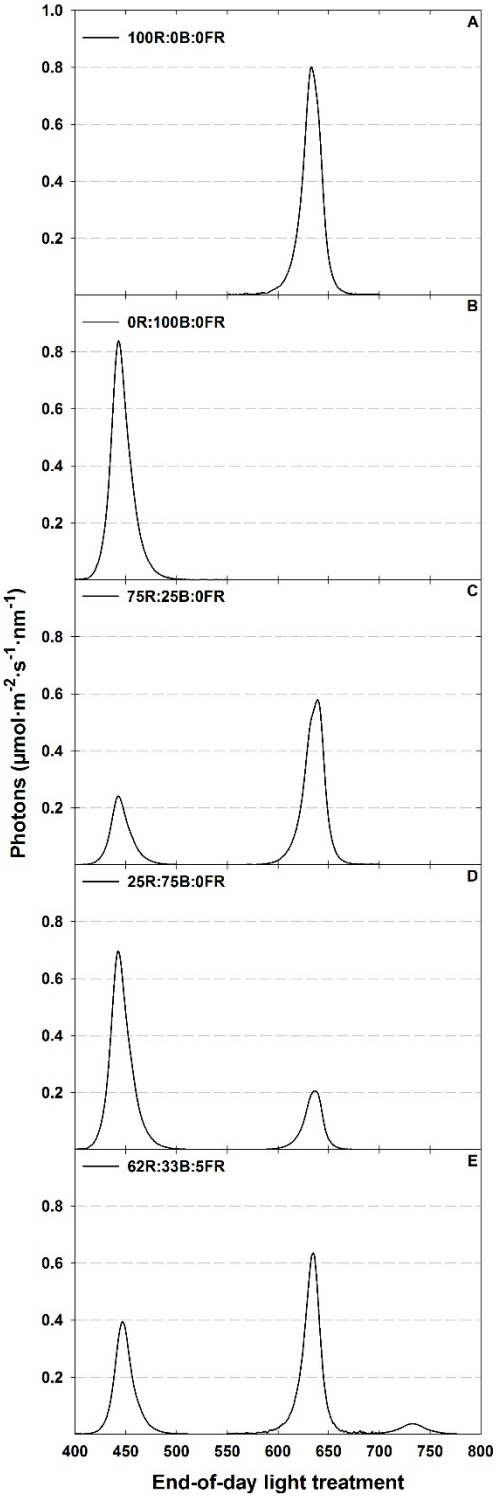

Figure 3.2. (A−E) Spectral quality of end-of-day light treatments delivering 20 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from light-emitting diodes providing (%) 100:0:0, 0:100:0, 75:25:0, 25:75:0, or 62:33:5 R:B:FR.

Plant measurements.

Stem length from the medium to the apical meristem of ten randomly selected seedlings from each tray was recorded on day 0, 7, 14, and 21 (Expt. 1). On day 21 (Expt. 1 and 2), stem length (measured from base of the hypocotyl to the shoot apical meristem) and stem caliper were measured with a digital caliper (digiMax; Wiha, Schonach, Germany) and recorded. After nondestructive measurements were recorded, medium was rinsed off the roots, roots were excised, and roots and shoots were dried separately in an oven at 70 °C for 4 d, then weighed. The ratio of root dry mass (RDM) to shoot dry mass [SDM (root:shoot)], sturdiness quotient [SQ (stem length/stem caliper)] (Thompson, 1985), and quality index, or QI [total dry mass × (root:shoot + sturdiness quotient)] (Currey et al., 2013) were calculated.

Plants in the finishing environment were monitored daily, and time to visible bud (TVB) from the time plants were placed in the finishing environment was recorded. Upon first open flower with fully reflexed petals, time to flower (TTF) from transplant, the number of nodes below the first open flower, and plant height from the medium to the apical meristem of the tallest shoot were recorded.

Statistical analysis.

Experiments were laid out in a randomized complete block design replicated over three seasons for Expt. 1 and repeated over two seasons for Expt. 2. Light treatments were re-randomized between seasons. There were ten samples (individual plants) per treatment for seedling and finish environments; seasons I, II, and III (Expt.1) and seasons I and II (Expt. 2) were pooled together. Samples in the finish environment were

completely randomized. Analysis of variance was performed using SAS PROC GLM (SAS 9.3; SAS Institute Inc., Cary, NC).

Results

Expt. 1. End-of-day red and far-red lighting.

Stem length after 7 d.

Stem length of *Cosmos*, *Pelargonium, Petunia*, and *Tagetes* were significantly influenced by EOD treatment (Fig. 3 A–E). For example, stem length of *Pelargonium* and *Tagetes*, respectively, was 21% and 25% lower under LED EOD lighting providing a R:FR ≈212 than under a R:FR ≈0.9. Stem length of *Cosmos* and *Petunia* was 22% and 75% lower under LED EOD lighting delivering a R:FR ≈212 compared to the INC lamps and CFL lamps, respectively. Stem length of *Impatiens* was not significantly influenced by EOD lighting.

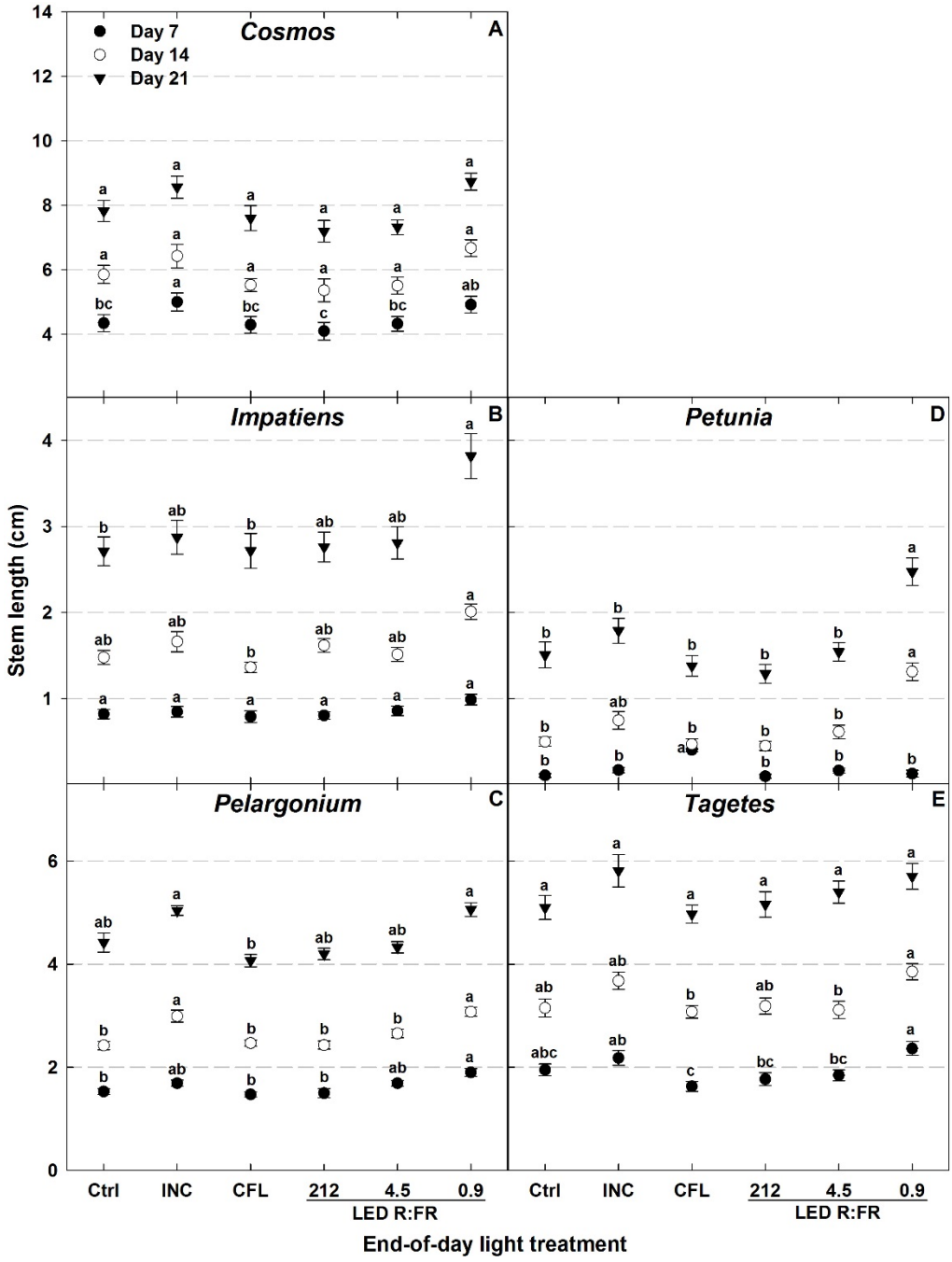

Figure 3.3. (A–E) Effect of no end-of-day (EOD) lighting (Ctrl) or 30 minutes of EOD lighting delivered from incandescent lamps, compact fluorescent lamps (CFL), or light-emitting diodes (LEDs) providing a red:far-red (R:FR) ratio of 212, 4.5 or 0.9 during seedling production on stem length of *Cosmos*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* on days 7, 14, and 21. Different lower-case letters across end-of-day light treatments within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Stem length after 14 d.

Stem length of *Impatiens*, *Pelargonium*, *Petunia,* and *Tagetes* was significantly influenced by treatment (Fig. 3 A–E). For instance, *Impatiens* stem length was reduced by 32% under CFL lamps compared to LEDs providing a R:FR ≈0.9. Stem length of *Pelargonium* and *Petunia* was reduced by 21%, 20%, 21%, and 14% and 62%, 64%, 66%, and 53%, respectively, under the control, CFL lamps, and LED treatments providing R:FR ≈212 and ≈4.5 compared to the LEDs providing R:FR ≈0.9. *Tagetes* stem length was reduced by 20% and 19% under CFL lamps and the LED treatment providing R:FR ≈4.5, respectively, compared to the LED treatment providing R:FR ≈0.9. *Cosmos* stem length was not influenced by treatment.

Stem length d 21.

Stem length of *Impatiens*, *Pelargonium*, and *Petunia* were all significantly influenced by treatment (Fig. 3 A–E). For example, stem length of *Impatiens* was reduced by 29% under both the control and CFL treatments compared to the LED treatment providing R:FR ≈0.9. Stem length of *Pelargonium* was reduced by 20% under CFL lamps compared to the LED treatment delivering R:FR ≈0.9. Stem length of *Petunia* was reduced by 39%, 44%, 27%, 47% and 38% under the control, CFL, INC, and LED treatments providing R:FR ≈212 and ≈4.5 compared to the LED treatment providing R:FR ≈0.9. *Cosmos* and *Tagetes* were not significantly affected by EOD treatment.

Root dry mass.

Petunia RDM was significantly influenced by treatment (data not shown). Root dry mass was 50% and 52% lower under LED treatments providing R:FR ≈212 and ≈4.5,

respectively, than under INC lamps. However, RDM of *Cosmos*, *Impatiens*, *Pelargonium*, and *Tagetes* was not significantly affected by EOD lighting.

Sturdiness quotient.

The SQ of *Pelargonium* and *Petunia* was significantly affected by EOD lighting (Fig. 4). For example, the SQ of *Pelargonium* was 17%, 19%, and 18% lower under the control, CFL, and LED treatment providing R:FR ≈212, respectively, compared to the R:FR ≈0.9 LED treatment. Sturdiness quotient of *Petunia* was 50% lower under the R:FR ≈212 LED treatment compared to the 0.9 R:FR treatment. *Cosmos*, *Impatiens*, and *Tagetes* SQ was not significantly affected by EOD treatment.

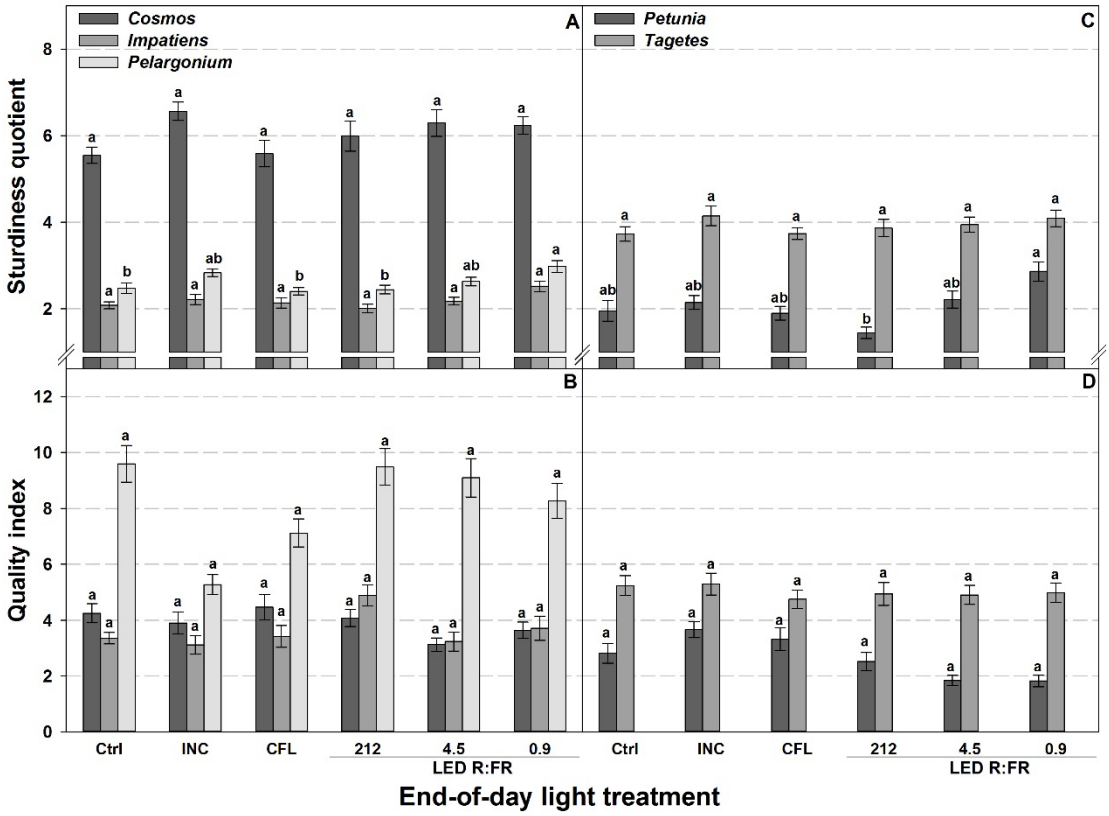

Figure 3.4. (A–D) Effect of no end-of-day (EOD) lighting (Ctrl.) or 30 min of EOD lighting delivered from compact fluorescent lamps (CFL), incandescent lamps (INC), or light-emitting diodes (LEDs) providing a red:far-red (R:FR) ratio of 212, 4.5 or 0.9 during seedling production on stem length, sturdiness quotient, and quality index of *Cosmos*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* on day 21. Different lower-case letters across end-of-day light treatments within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Stem caliper, SDM (data not shown), and QI (Fig. 4) were not significantly influenced after 21 d of EOD lighting. Stem length at flower, TVB, TTF, and nodes below the first open flower (data not shown) were not significantly influenced by seedling EOD lighting.

Expt. 2. End-of-day red, blue, and far-red lighting.

Stem length.

After 21 d, *Petunia* was the only species where stem length was affected by EOD lighting (Fig. 5). For example, stem length was 11%, 11%, and 10% lower under EOD lighting providing (%) 100:0:0, 75:25:0 and 25:75:0 R:B:FR, respectively, compared to EOD lighting providing 62:3:5 R:B:FR.

Sturdiness quotient, QI (Fig. 5), RDM, SDM, SC, height at flower, TVB, TTF, and nodes below flower (data not shown) were not significantly influenced by seedling EOD lighting.

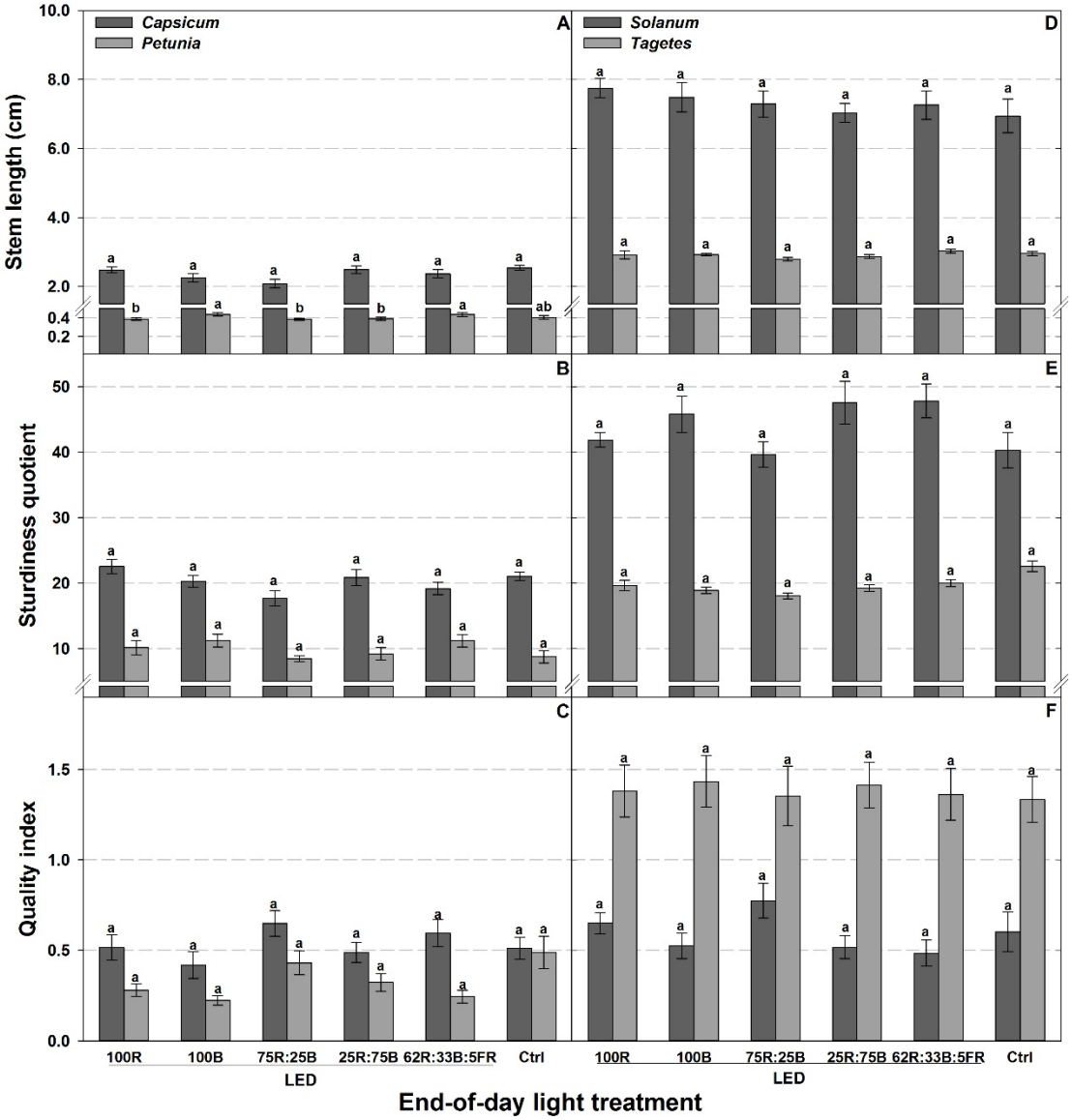

Figure 3.5. (A–F) Effect of end-of-day light providing ≈20 µmol·m^{-2}·s^{-1} from light-emitting diodes (LEDs) delivering (%) 100:0:0, 0:100:0, 75:25:0, 25:75:0, or 62:33:5 R:B:FR light ratios during seedling production on stem length, sturdiness quotient, and quality index for *Capsicum*, *Petunia*, *Solanum*, and *Tagetes* on day 21. Different lower-case letters across end-of-day light treatments within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Discussion

Several factors contribute to high-quality bedding plants, including height, sturdiness, and dry mass. Results from Expt. 1 indicate that stem length of *Cosmos*, *Impatiens*, *Pelargonium*, and *Petunia* can be reduced using a high R:FR ratio. For instance, *Pelargonium* stem length was reduced by 22%, 20%, and 20% under a R:FR ≈8.4 (CFL) after 7, 14, and 21 d of EOD lighting, respectively, compared to a R:FR ≈0.9. Additionally, *Petunia* stem length was reduced under all treatments delivering a R:FR ≥ 4.5 after 14 and 21 d of EOD lighting. Other investigations have shown that shade avoidance is a phytochrome-mediated response to avoid shading, crowding and competition with other plants (Franklin, 2008). After 7 and 14 d, seedlings were not large enough to cause plant-to-plant shading; but by 21 d under EOD lighting, the canopy had closed. As a result, the effects of a low R:FR became less pronounced. For example, stem length of *Tagetes* was 25% and 19% shorter under LEDs providing a R:FR ≈212 compared to R:FR ≈0.9 after 7 and 14 d, respectively. However, by 21 d, no EOD treatment significantly influenced stem length, indicating the shade avoidance response had overcome any positive treatment response. Conversely, results from Expt. 2 indicate there were no significant differences between seedlings provided with EOD R, R + B, or R + B + FR light.

In contrast, when *Citrulls* [*Citrullus lanatus* (Thunb.) Matsum and Nakai 'Sugar Baby'] seedlings were provided with 15 min of EOD lighting consisting of R or FR light, stem length was reduced by 20% and 31% after 7 and 21 d under R light compared to FR light (Decoteau and Friend, 1991). Another study used FR blocking film in low tunnels on bench tops to compare height and yield quality of *Solanum* (*S. lycopersicon* L.)

seedlings. Seedlings grown under FR blocking film were ≈22%, 19%, and 19% shorter than plants grown without film after 7, 14, and 21 d, respectively (Evans and McMahon, 2004). Similarly, a study by Ranwala and Decoteau (2007) indicated that when *Citrulls* (*C. lanatus* (Thunb.) Matsum and Nakai 'Sugar Baby') seedlings were grown under a 12-h photoperiod with 15 min EOD lighting of either R, FR, or 15 min FR followed by 15 min R light, internode length was reduced for all treatments compared to the EOD FR light treatment.

Conversely, when seedlings of *Cucumis* 'Erles Knight Natsu No. 2' (*Cucumis melo* L. 'Erles Knight Natsu No. 2'), and *Cucumis* 'Rensei' (*Cucumis sativus* L. 'Rensei') were grown under films transmitting R:FR ≈0.6, ≈1.0, and ≈2.2, SDM and RDM was similar across all treatments for *C.* 'Erles Knight Natsu No. 2' while *C.* 'Rensei' SDM was reduced by ≈10% and ≈20% in plots under the filters transmitting R:FR ≈0.6 and ≈2.2, respectively, compared to R:FR ≈1.0 (Takaichi et al., 2000). In the present study, similar trends were observed as RDM was 50% and 52% lower in only *Petunia* receiving a high R:FR ratio ≈212 and ≈4.5 compared to ≈0.8 (Expt. 1). Similarly, another study found no significant differences in total dry mass or stem caliper of *Solanum* (*S. lycopersicum* L. 'Aloha' and *S. lycopersicum* L. ×*habrochaites* Knapp and Spoone 'Maxifort') grown under EOD treatments providing varying doses and durations of R:FR ≈0.05 (Chia and Kubota, 2010). However, in Expt. 1 the SQ of *Pelargonium* and *Petunia* decreased as the R:FR ratio increased from ≈0.9 to 212, indicating height decreased relative to stem caliper resulting in higher quality seedlings.

Other studies have investigated the effects of providing FR light from different light sources during the finish stage to promote or inhibit flowering (Blom et al., 1995; Craig and Runkle, 2013; Ilias and Rajapakse, 2005; Padhye and Runkle, 2011; Runkle et al., 2012). One study compared INC lamps with CFL lamps providing a truncated 9-h day with night interruption (NI) or day extension (DE) lighting. Flowering of *Petunia* (*P.* 'Wave Purple Classic') was delayed 2 to 3 weeks when plants were grown with 4 h NI and 6 h DE under CFL lamps compared to INC lamps. The same study found that *Campanula* (*Campanula carpatica* Jacq. 'Pearl Deep Blue'), *Chrysanthemum* (*C.* ×*grandiflorum* Ramat. 'Auburn'), *Coreopsis* (*Coreopsis grandiflora* Hogg ex Sweet 'Early Sunrise'), and *Rudbeckia* (*Rudbeckia hirta* L. 'Beck Cinnamon Bicolor') flowering percentage was not influenced by bulb type (Runkle et al., 2012). Similarly, when *Petunia* (*P.* 'Countdown Burgundy') were grown under a natural photoperiod of 10.5 h plus a 15 min EOD treatment providing R:FR light of 0.67, 1.05, or 1.51. Flowering was delayed by 11 d under the R:FR =1.51 compared to the no EOD control, but the R:FR =0.67 had no effect (Ilias and Rajapakse, 2005). None of the EOD treatments in the current study had any significant effects on subsequent flowering, indicating that use of EOD FR light during seedling production does not influence flowering. However, the use of FR light during the finish stage can promote flowering of LD plants and inhibit flowering of SD plants. Although FR light can be used later in production to promote flowering, timing is important to avoid excessive stretch in finished plants (Ilias and Rajapakse, 2005).

Clifford et al. (2004) demonstrated how stem length of *Euphorbia* [*Euphorbia pulcherrima* Willd. ex Kloczsch. 'Spotlight' (Expt. 1) and 'Freedom Red' (Expt. 2)]

responds to R:FR. Plants in Expt. 1 were grown under a FR light blocking filter (R:FR =2.04), neutral shading material (control), or were treated with the plant growth regulator (PGR) chlormequat chloride [Cycocel (1.5mL·L^{-1}, 46% a.i.)]. Height of *E*. 'Spotlight' grown under the FR-blocking filter or treated with the PGR were 24% and 28% shorter, respectively, than under the neutral control. Plants in Expt. 2 were grown under FR, R, or B-light-blocking filters. The internode length was reduced by 20% under the filter blocking FR light, but increased by 71% and 9% under the filters blocking R and B light, respectively, compared to the neutral control. Similarly, our study showed that stem length was impacted by the R:FR ratio during seedling EOD lighting; however, final height at flower was not significantly influenced by EOD lighting during the seedling phase.

Although temperature was not a focus of this study, it has been suggested that temperature interacting with light quality can be effectively used to control stem length of seedlings (Blom et al., 1995; Weinig, 2000; Xiong et al., 2002). For example, *Abutilan* (*Abutilan theophrasti* Medik.) were used to observe how temperature, photoperiod, and maternal environment affect stem length under R:FR ≈0.4 and ≈1.3 light. There was a strong light-quality × temperature interaction such that hypocotyl elongation was enhanced under a low R:FR ratio (≈0.4) and high temperature (day/night set point of 26/20 °C) compared to a high R:FR ratio (≈1.3) and low temperature (day/night set point of 18/16 °C). Plants grown under the low R:FR were 134% taller than plants grown under a high R:FR ratio while plants grown at high temperatures were 72% taller than plants grown at lower temperature (Weinig, 2000). Another study used a long-hypocotyl phytochrome B deficient mutant (*lh*) and wild type (WT) of *Cucumis* (*C. sativus* L.)

grown in growth chambers to compare the effect of temperature and light quality on stem length. Treatments included a 12-h day with day/night temperature of 25/19 °C or 19/25 °C and EOD lighting provided either FR or R light for 30 min. Wild-type plants grown under EOD FR light were 68% and 41% taller under the 25/19 °C and 19/25 °C while the *lh* mutant showed little response. However, under EOD R light, there was little difference between the two temperatures (Xiong et al., 2002).

End-of-day lighting using a high R:FR ratio can be used to control stem elongation in some herbaceous annual bedding plant species. Other quality parameters such as stem caliper, SQ, RDM, SDM, and QI were affected by EOD light in Expt. 1, but were marginally effective in Expt. 2. Our results indicate that effects of EOD light treatments for seedlings can be species specific. Additionally, EOD treatment did not carry over from the seedling environment to the finish environment. Low-intensity EOD light can be used to enhance or suppress stem elongation during seedling production without negatively impacting subsequent flowering. However, the use of NI or DE extension could be used to prevent or promote flowering during the finish stage.

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COMPARING SUPPLEMENTAL AND SOLE SOURCE LIGHTING FOR BEDDING PLANT SEEDLING PRODUCTION

Introduction

Young plants are commonly produced from vegetative cuttings or seeds during late winter and early spring (Klopmeyer et al., 2003; Styer, 2003). However, during peak young plant production the average greenhouse photosynthetic daily light integral (DLI) can be as low as 1 to 5 $mol \cdot m^{-2} \cdot d^{-1}$ in northern latitudes leading to decreased plug quality (Faust et al., 2005; Lopez and Runkle, 2008; Pramuk and Runkle, 2005). It has been shown that a DLI of 10 to 12 $mol \cdot m^{-2} \cdot d^{-1}$ is an acceptable minimum recommendation for young plant production (Currey et al., 2012; Faust et al., 2005; Fisher and Both, 2004; Hutchinson et al., 2012; Lopez and Runkle, 2008; Oh et al. 2010; Pramuk and Runkle, 2005; Randall and Lopez, 2014; Runkle, 2007). The only way to appreciably increase DLI during young plant production is through the use of supplemental lighting (SL) (Oh et al., 2010; Randall and Lopez, 2014; Sherrard, 2003).

High-intensity discharge lamps such as high-pressure sodium (HPS) and metal halide lamps have traditionally been used for SL to increase DLI. High-pressure sodium lamps have long been the most efficient SL source, converting ≈25% to 30% of their electrical energy into photosynthetically active radiation [PAR (400–700 nm)], and having an operational lifespan of 10,000 h or more. However, as much as 72% of the PAR light emitted by HPS lamps is in the 565–590 nm (yellow) and 590–625 nm (orange)

wavebands. Moreover, of the electrical energy used by HPS lamps, up to 75% is emitted as radiant heat, and the surface temperature of the bulb can reach temperatures as high as 450 °C, requiring plants to be separated from the lamps to avoid leaf scorch (Fisher and Both, 2004; Sherrard, 2003; Spaargaren, 2001).

In recent years, a number of alternatives to HPS lamps have surfaced, including plasma lamps (PL) and high intensity light-emitting diodes (LEDs). Plasma lamps are electrodeless and generate a continuous spectrum of light by exciting sulfur or halide molecules in the lamp using an excitation source such as a magnetron or radio frequency generator. They are considered efficient light sources because they convert 70% of the electrical energy delivered to the plasma into visible light. However, a tremendous amount of heat can be emitted from the lamps (≈900 °C) requiring significant cooling and separation from the crop (Sager and Wheeler, 2012).

Alternatively, LEDs are solid-state, single junction semiconductors that are capable of producing light wavelengths as short as 250 nm to greater than 1000 nm, useful for testing specific wavelength combinations for plant growth and morphology (Folta and Childers, 2008; Stutte, 2009). Until recently, LEDs were low power (<1 W) and impractical for SL (Bourget, 2008). However, as LEDs have become more efficient [38% (red) – 50% (blue)] and capable of high outputs (>1 W), they have become considerable sources for both sole-source lighting (SSL) and SL (Barta et al., 1992; Bula et al., 1991; Massa et al., 2008; Morrow, 2008, Philips Lumileds, 2011). In addition to their high efficiency, LEDs offer an estimated lifetime of 50,000 luminous hours (Bourget, 2008). Finally, LEDs do not radiate heat towards the plant canopy, allowing lights to be placed close to crops. However, heat is still produced by the electricity running across the

junction, which can reduce the life and efficiency of the LED. As a result, the need for heat dissipation without significant shading poses challenges for LEDs developed for greenhouse use (Bourget, 2008; Christensen and Graham, 2009).

Due to their small size, wavelength specificity, high light output, and relatively low heat output, LEDs have been used in growth chambers as SSL (Wollaeger, 2013; Wollaeger and Runkle, 2013), or in greenhouses as overhead SL (Currey and Lopez, 2013; Randall and Lopez, 2014) for young plants. For example, seedlings of *Ageratum houstonianum* Mill. 'Blue Field', *Salvia splendens* F. Sello ex Ruem and Schult. 'Red Vista', and *T. erecta* L. 'Orange Boy' were grown under SSL for 28 d at 25 ± 2 °C and 60 ± 10% relative humidity (RH) using LEDs delivering a 16-h photoperiod with a *PPF* of 90 ± 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (DLI ≈5 $mol \cdot m^{-2} \cdot d^{-1}$) at a 1:1 ratio of red:blue, blue:far-red, or red:far-red light, or cool-white fluorescent lamps as a control. After 28 d, leaf area of *Ageratum* and *Salvia* grown under the red:blue LEDs increased by 100–122% and 42–66%, respectively, than other LED treatments and was similar to the control. Additionally, height of *Agerantum*, *Salvia*, and *Tagetes* was reduced by 35–69%, 57–64%, and 44–56%, respectively, under the red:blue LEDs compared to the other LED treatments while remaining similar to the control (Heo et al., 2006). Another study compared seedlings of *Impatiens* 'SuperElfin XP Red', *Petunia* 'Wave Pink', *Solanum lycopersicum* L. 'Early Girl', and *Tagetes* 'Deep Orange' grown under SSL with a 18-h photoperiod and *PPF* of 160 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (DLI ≈9 $mol \cdot m^{-2} \cdot d^{-1}$) delivered from LEDs providing 10% blue and 10% green light with the following combinations (%) of orange (596 nm), red (634 nm), and hyper-red (664 nm) light: 20:30:30, 0:80:0, 0:60:20, 0:40:40, 0:20:60, 0:0:80. Leaf number was similar among all treatments; and leaf area

was similar among all treatments except *Solanum* which was lower under the 0:0:80 orange:red:hyper-red light treatment than three of the four treatments providing ≥30% red light. The effect of light treatment on height and dry mass varied by species. For instance, height of *Solanum* and *Tagetes* was 18% and 13% shorter under the 0:40:0 than 0:80:0 orange:red:hyper-red treatment, respectively, but similar to the other light treatments; and shoot dry mass of *Solanum* was 25–40% greater under the 0:60:20 orange:red:hyper-red than the light treatments providing 0:40:40, 0:20:60, or 0:0:80 orange:red:hyper-red light (Wollaeger and Runkle, 2013). Finally, Randall and Lopez (2014) compared seedlings of *Antirrhinum majus* L. 'Rocket Pink', *Catharanthus roseus* L. G. Don 'Titan Punch', *Celosia* 'Fresh Look Gold', *Impatiens* 'Dazzler Blue Pearl', *Pelargonium* ×*hortorum* L.H. Bailey 'Bullseye Scarlet', *Petunia* 'Plush Blue', *Salvia* 'Vista Red', *Tagetes* 'Bonanza Flame' and *Viola* ×*wittrockiana* Gams. 'Mammoth Big Red' grown under ambient solar light supplemented with a 16 h photoperiod and *PPF* of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ delivered from either HPS or one of three LED arrays comprised of (%) 100:0, 85:15, or 70:30 red:blue light. After 28 d under treatment, height of all species except *Antirrhinum* and *Pelargonium* was reduced by 9–55% under 85:15 red:blue LED SL compared to HPS SL treatments; and stem caliper of *Antirrhinum*, *Pelargonium*, and *Tagetes* was 8–16% greater under 85:15 red:blue LEDs compared to seedlings grown under HPS lamps.

To our knowledge, no studies have compared annual bedding plant seedlings grown in a growth chamber under vertical SSL to those grown under SL in a greenhouse providing the same DLI. The objectives of this study were to: 1) quantify the effects of SL from HPS lamps, PL lamps, and LED arrays in a greenhouse on growth, morphology, and quality; 2) quantify the effects of SSL in a vertical growth chamber production

system from two different LED light qualities on growth, morphology, and quality; 3) compare seedlings grown under SL and SSL to seedlings grown under ambient solar light; and 4) determine whether there were any residual effects of either SSL or SL on finished plant quality.

Materials and Methods

Plant material, culture, and propagation environment.

Seeds of *Catharanthus* 'Titan Red Dark', *Impatiens* 'Super Elfin XP Blue Pearl', *Pelargonium* 'Bullseye Red', *Petunia* 'Dreams Midnight', and *Tagetes* 'Durango Yellow' (Ball Horticulture, West Chicago, IL) were sown into 288-cell (6-ml individual cell vol.) seed trays filled with a commercial soilless medium comprised of (by vol.) 65% peat, 20% perlite, and 15% vermiculite (Fafard Super Fine Germinating Mix; Fafard, Inc., Agawam, MA) and placed in a glass-glazed greenhouse at Purdue University, West Lafayette, IN (lat. 40 °N). Exhaust fan and evaporative-pad cooling, radiant hot water heating, and retractable shade curtains were controlled by an environmental control system (Maximizer Precision 10; Priva Computers Inc., Vineland Station, Ontario, Canada). The daily light integral (DLI) and average daily temperatures (ADT) for seasons I, II and III from sowing to hypocotyl emergence were 12.1 ± 1.7, 11.4 ± 2.8, and 13.3 ± 1.8 $mol \cdot m^{-2} \cdot d^{-1}$, and 22.6 ± 0.8 °C, 22.3 ± 1.1 °C, and 22.4 ± 1.1 °C, respectively. Upon hypocotyl emergence, two trays of each species were moved under lighting treatments in either a glass-glazed greenhouse or a growth chamber.

Greenhouse environment.

All species were placed under a 16-h photoperiod with ADTs of 22.6 ± 0.9, 22.7 ± 0.7, and 22.7 ± 2.8 °C. Infrared temperature sensors (OS136, Omega Engineering, Inc.,

Stamford, CT) recorded seedling canopy temperatures every 30 s and averages were logged every 15 min by a data logger (Maximizer Precision 10). Quantum sensors (SQ-110, Apogee Instruments Inc., Logan UT) measured solar *PPF* every 15 s and the average was logged every 15 min by a data logger (WD 2800, Spectrum Technologies, Aurora, IL). Environmental data are reported in Table 1. Seedlings were irrigated with water-soluble fertilizer (Jack's LX 16N–0.94P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) providing (in $mg \cdot L^{-1}$): 100 N, 10 P, 78 K, 18 Ca, 9.4 Mg, 0.10 B, 0.05 Cu, 0.50 Fe, 0.25 Mn, 0.05 Mo, and 0.25 Zn.

Table 4.1. Average greenhouse plant canopy and air temperatures, relative humidity, and daily light integral (DLI) under ambient solar daylight supplemented with approximately 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$ from high-pressure sodium (HPS) lamps, plasma (PL) lamps, or light-emitting diodes (LEDs; 88:12 red:blue light) from 0600 to 2200 HR. *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* were placed under treatments on 01 Oct. 2013, 04 Nov. 2013, and 13 Jan. 2014.

Treatment initiation	Supplemental light source	Supplemental light ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Total DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Relative humidity (%)	Leaf canopy temperature (°C)
01 Oct. 2013	Ambient	--[z]	4.6 ± 1.4	74.6 ± 22.0	21.1 ± 1.9
	HPS	73.2 ± 34.6	8.6 ± 1.7		21.4 ± 1.3
	LED	71.0 ± 13.4	8.5 ± 1.7		21.9 ± 1.5
04 Nov. 2013	Ambient	--	6.3 ± 3.1	71.8 ± 15.3	18.8 ± 1.6
	HPS	70.9 ± 28.4	10.4 ± 3.1		20.4 ± 1.2
	LED	69.8 ± 12.6	10.3 ± 3.1		20.5 ± 1.4
13 Jan. 2014	Ambient	--	6.7 ± 2.8	73.2 ± 15.3	17.6 ± 2.5
	HPS	72.7 ± 30.0	10.9 ± 2.8		19.6 ± 1.8
	LED	73.0 ± 10.4	10.9 ± 2.8		20.3 ± 1.8
	PL	71.5 ± 22.6	10.8 ± 2.8		20.8 ± 2.7

[z]No supplemental light provided

Growth chamber environment.

All species were placed in a walk-in growth chamber (C5 Control System, Environmental Growth Chambers, Chagrin Falls, OH) with ADT of 23.0 ± 0.1, 23.0 ± 0.1, and 23.0 ± 0.1 °C under a 16-h photoperiod. Air temperature, relative humidity, and carbon dioxide (CO_2) were logged every 15 min by a data logger (DL1 Datalogger, Environmental Growth Chambers). Environmental data are reported in Table 2. Seedlings were irrigated with the same fertilizer used in the greenhouse environment.

Table 4.2 Average growth chamber daily light integral (DLI), relative humidity, carbon dioxide (CO_2), and sole-source light of approximately 185 $\mu mol \cdot m^{-2} \cdot s^{-1}$ delivered from LEDs with varying proportions of red (R) and blue (B) light from 0600 to 2200 HR. *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* were placed under treatments on 01 Oct. 2013, 04 Nov. 2013, and 13 Jan. 2014.

Treatment initiation	LED sole-source light	Light intensity ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Relative humidity (%)	CO_2 (ppm)
01 Oct. 2013	88R:12B	184.6 ± 44.1	10.6	70.5 ± 6.6	491.7 ± 47.3
	70R:30B	185.7 ± 55.4	10.7		
04 Nov. 2013	88R:12B	183.2 ± 40.6	10.6	72.8 ± 4.5	497.9 ± 12.6
	70R:30B	183.5 ± 51.2	10.6		
13 Jan. 2014	88R:12B	184.1 ± 37.3	10.6	73.1 ± 4.6	507.6 ± 48.2
	70R:30B	181.6 ± 49.3	10.5		

Lighting treatments.

Seedlings in the greenhouse were grown under ambient solar light supplemented with ≈70 μmol·m^{-2}·s^{-1} *PPF* at plant height [as measured with a spectroradiometer (PS-100; Apogee Instruments, Logan, UT)] from 0600 to 2200 HR (Table 1) or no SL (control) for 21 d (*Pelargonium* and *Tagetes*) or 28 d (*Catharanthus*, *Impatiens*, and *Petunia*). Supplemental light was delivered from either two 150-W HPS lamps (PL 2000, P.L. Light Systems Inc., Beamsville, ON, Canada), two 300-W PL lamps (Solar Genesis-I, Chameleon Grow Systems, Ocoee, FL), or eight 32-W LED arrays [120 cm-long 4cm-wide (Philips GreenPower LED production module; Koninklijke Philips Electronics N.V., Netherlands)] spaced on 44.5 cm centers 78.7 cm above the bench top providing (%) 88:12 red (660 nm) blue (460 nm) light (SL88:12).

Seedlings in the growth chamber were grown under a vertical production system with SSL LEDs providing ≈185 μmol·m^{-2}·s^{-1} *PPF* at plant height [as measured with a spectroradiometer (Apogee Instruments) from 0600 to 2200 HR (Table 2) for the same number of days as the plants in the greenhouse. Light was delivered from one of two LED arrays providing 88:12 red:blue light [SSL88:12 (Philips GreenPower LED production module)] spaced on 20.4 cm centers, or 70:30 red (660-nm):blue light (460-nm) (SSL70:30) [48.5 cm-long and 3.3 cm-wide (Philips GreenPower LED research module; Koninklijke Philips Electronics N.V.)] spaced on 7.6 cm centers. Three SSL88:12 LEDs or 16 SSL 70:30 LEDs were mounted to steel shelves (121 cm-long and 61 cm-wide) comprised of three vertical layers spaced 45.7 cm and 50.8 cm apart for the 88:12 and 70:30 LEDs, respectively. Spectral scans of SSL and SL were taken at night at the beginning of each replication with a spectroradiometer (PS-100; Apogee Instruments).

Spectral quality of light sources is shown in Fig. 1. Electrical use for HPS lamps, LEDs, and PL lamps were measured in the greenhouse environment using an electrical meter (P440 Kill A Watt; P3 International, New York, NY).

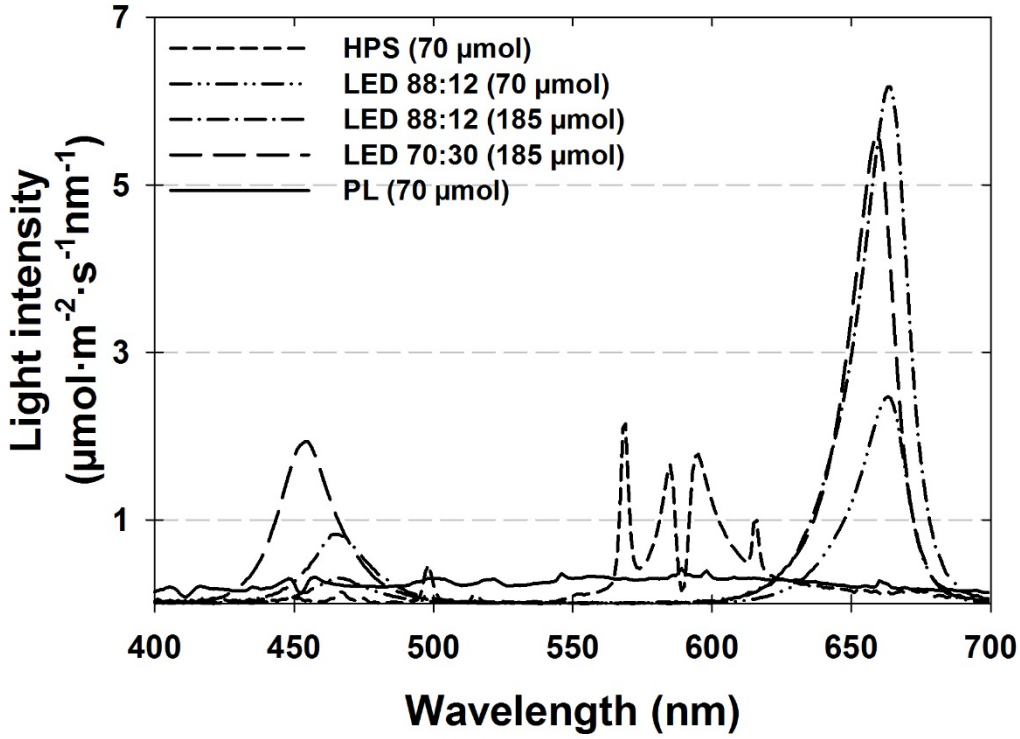

Figure 4.1. Light quality of high-pressure sodium (HPS) lamps, plasma lamps (PL), and light-emitting diodes (LEDs) delivering (%) 88:12 red:blue light emitting a *PPF* of 70 $\mu mol \cdot m^{-2} \cdot s^{-1}$, or LEDs delivering 88:12 and 70:30 red:blue light emitting a *PPF* of 185 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at canopy level.

Finishing culture and environment.

At the end of greenhouse and growth chamber lighting treatments, 10 randomly selected seedlings from each tray were transplanted into 11.4-cm (600-mL) containers (Dillen Products, Middlefield, OH) filled with a commercial soilless medium comprised of (by vol.) 65% peat, 20% perlite, and 15% vermiculite (Fafard 2; Fafard, Inc.). Plants were placed in a common finish environment with a 16-h photoperiod of ambient light

supplemented with a *PPF* of ≈70 µmol·m^{-2}·s^{-1} from HPS lamps to provide a DLI of 9.2 ± 6.9, 11.2 ± 7.6, and 12.6 ± 1.6 mol·m^{-2}·d^{-1}. Air temperatures in the finishing environment were 19.3 ± 2.3, 19.2 ± 2.0, 19.3 ± 1.8 °C. Plants were irrigated as necessary with acidified water supplemented with a combination of two water-soluble fertilizers (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris, Marysville, OH) to provide the following (mg·L^{-1}): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.24 Cu and B, and 0.1 Mo.

Data collection and calculations.

At 14, 21, and 28 d after initiating SL and SSL treatments, 25 plants of each species were randomly harvested and measured for pullability (the number of seedlings that can be pulled from the tray with roots and media intact). The collective roots and shoots of the 25 plants were washed and placed in a drying oven at 70 °C. After 4 d, roots and shoots were weighed to determine collective root dry mass (RDM) and shoot dry mass (SDM), respectively.

At 21 (*Pelargonium* and *Tagetes*) or 28 d (*Catharanthus*, *Impatiens*, and *Petunia*) after initiating SL and SSL treatments, 10 plants from each species were randomly selected and measured for height (measured from the base of the hypocotyl to the shoot apical meristem), leaf number, and stem caliper above the lowest leaf with a digital caliper (digiMax; Wiha, Schonach, Germany) were recorded. Relative chlorophyll content was measured with a SPAD meter (SPAD-502; Konica Minolta Sensing, INC., Osaka, Japan). After nondestructive measurements were recorded, roots and shoots of all selected seedlings were washed and separated. Leaf area was taken using a leaf area meter (LI-3100, LI-COR Inc., Lincoln, NE) before placing roots and shoots in a drying

oven at 70 °C for at least 4 d, and RDM and SDM were recorded. The sturdiness quotient (SQ) was calculated as stem caliper divided by stem length. The quality index (QI), an objective, integrated, and quantitative measurement of quality, was calculated as the [total dry mass × (shoot:root ratio + sturdiness quotient)] (Currey et al., 2013).

Transplants in the finish environment were monitored daily following planting. When the first flower opened, the date, node number beneath the first open flower, and plant height from the surface of the medium to the top of the plant were recorded. Time to flower (TTF) was calculated as the time from transplant into the finish environment to the first flower opening.

Statistical analysis.

The experiment used a complete block design, replicated three times in time for each of the five species. There were ten samples (individual plants) per species per SSL and SL treatment for seedling and finish data. Data were analyzed using SAS (SAS 9.2; SAS Institute Inc., Cary, NC) mixed model procedure (PROC MIXED) for analysis of variance.

Results

Harvest d 14.

Pullability of *Catharanthus* was significantly affected by lighting treatment where 20% of seedlings harvested were pullable under the SSL70:30 LEDs compared to zero under the control. Pullability of other species was not significantly affected by lighting treatment. Collective RDM was significantly affected by light treatment for *Impatiens* and *Tagetes*, but not *Catharanthus*, *Pelargonium*, and *Petunia*. For example, collective RDM of *Impatiens* was 256% greater for seedlings grown under the SSL88:12 LEDs

compared to the control; and *Tagetes* collective RDM was 96% and 73% greater under the SSL70:30 LEDs compared to the control and SL88:12 LEDs. Collective SDM of *Impatiens* and *Pelargonium* was significantly influenced by light treatment, but the other species were not significantly influenced. Collective SDM of *Impatiens* was 244% and 224% and *Pelargonium* 73% and 80% greater under the SSL88:12 and SSL70:30 LEDs, respectively, compared to the control (data not shown).

Harvest d 21.

Pullability of *Petunia* was the only species influenced by light treatment where pullability increased by 82–106% for seedlings grown under HPS, SL88:12, SSL88:12, and SSL70:30 LEDs compared to the control. Collective RDM of *Impatiens* and *Petunia* increased by 216% and 151% for seedlings grown under the SSL70:30 LEDs compared to the control; and *Tagetes* increased by 160% and 99% under PL lamps compared to the control and SSL88:12 LEDs. However, *Catharanthus* and *Pelargonium* collective RDM was not influenced by light treatment. *Impatiens* and *Pelargonium* collective SDM increased by 227% and 71%, respectively, for seedlings grown under SSL70:30 LEDs compared to the control; however, the other species were not affected by light treatment (data not show).

Harvest d 28.

Pullability of *Catharanthus* was 24–28% greater for seedlings grown under HPS, SSL88:12, and SSL70:30 LEDs compared to the control; however *Impatiens* and *Petunia* were not significantly influenced by light treatment. Collective RDM was not significantly influenced by light treatment for any species. *Catharanthus* and *Impatiens* collective SDM was 189% and 191% greater, respectively, for seedlings grown under

SSL88:12 LEDs compared to the control. *Impatiens* collective SDM was not influenced by light treatment (data not shown).

Height.

Height of all species was affected by light treatments (Fig. 2A and B). For instance, height of *Catharanthus* was reduced by 21%, 24%, 17%, and 23% for seedlings grown under SL88:12 LEDs compared to HPS, SSL88:12, SSL70:30, and PL lamps, respectively, but similar to the control. Height of *Impatiens* was reduced by 29%, 18%, 26%, and 39% for the control compared to HPS, SL88:12, SSL88:12, and PL lamps, respectively; and seedlings grown under SSL70:30 LEDs were 18% shorter than under HPS lamps. *Pelargonium*, *Petunia*, and *Tagetes* height was reduced by 21% and 26%, 75% and 79%, and 18% and 16% for seedlings grown under SSL88:12 and SSL70:30 LEDs, respectively, compared to HPS lamps.

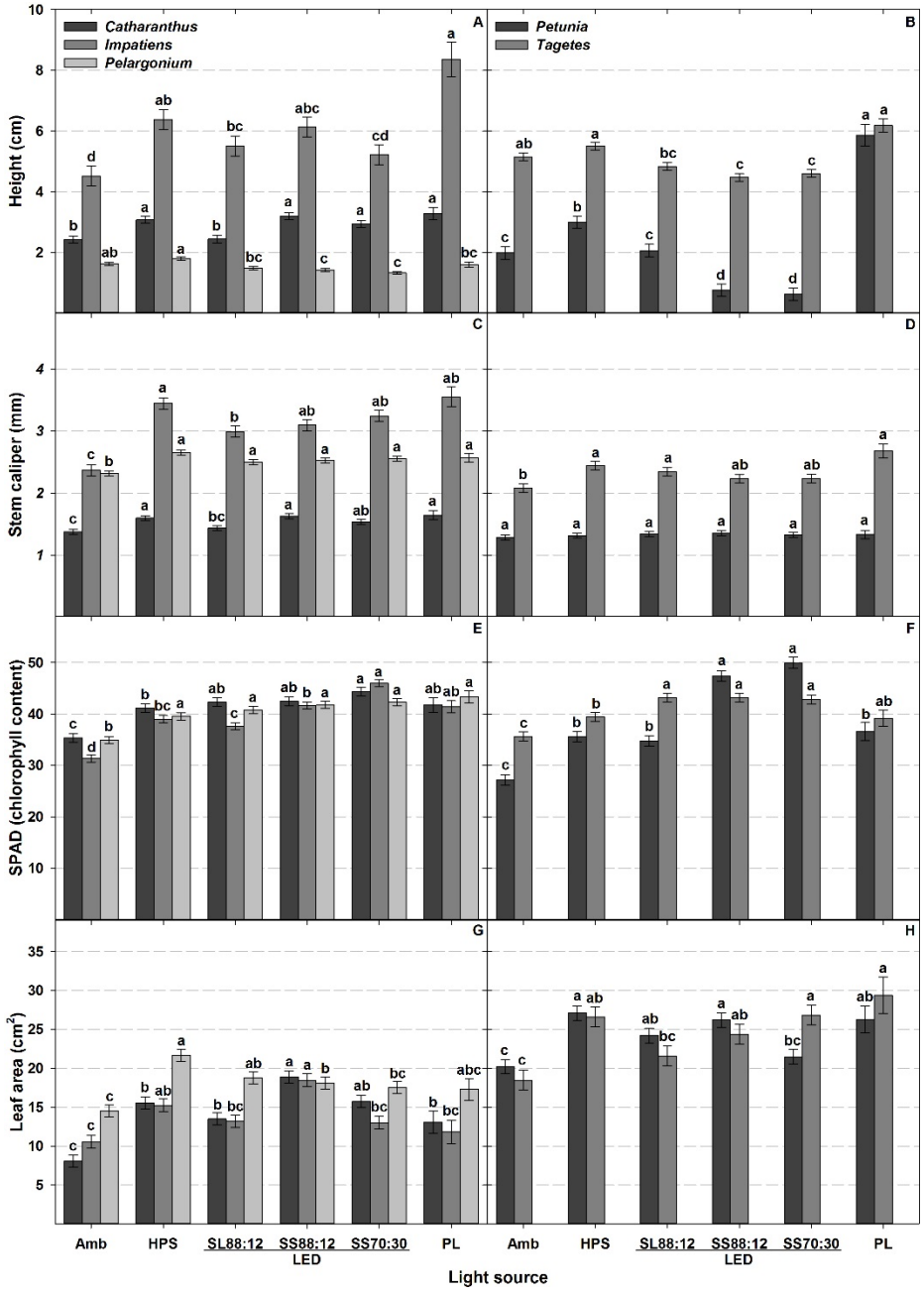

Figure 4.2. (A–H). Effect of ambient solar light (Amb); or 70 µmol·m^{-2}·s^{-1} of supplemental light (SL) delivered from high-pressure sodium (HPS) lamps, light-emitting diodes (LEDs; SL88:12), or plasma (PL) lamps; or 185 µmol·m^{-2}·s^{-1} of sole-source (SS) light delivered from LEDs (SS88:12 and SS70:30) during seedling production on height, stem caliper, relative chlorophyll content (SPAD), and leaf area of *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* after 21 or 28 d. Different lower-case letters across treatment source within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Stem caliper.

Stem caliper of all species with the exception of *Petunia* was affected by light treatments (Fig. 2C and D). For example, stem caliper of *Catharanthus* was 16%, 18%, 11%, and 20% greater for seedlings grown under HPS, SSL88:12, SSL70:30, and PL lamps, respectively, compared to the control. *Impatiens* and *Pelargonium* stem caliper was 26–46% and 8%–15% greater, respectively, under HPS, SL88:12, SSL88:12, SSL70:30, and PL lamps compared to the control. Stem caliper of *Tagetes* was 17%, 13%, and 16% greater under HPS, SL88:12, and PL lamps, respectively, compared to the control.

Relative Chlorophyll content.

Relative chlorophyll content of all species was significantly affected by light treatments (Fig. 2E and F). For example, relative chlorophyll content of *Catharanthus* was 25% and 16% higher under the SSL70:30 LEDs compared to seedlings under the control and HPS lamps, respectively; and *Impatiens* relative chlorophyll content was 10–47% greater under the SSL70:30 LEDs compared to the control, HPS, SL88:12, SSL88:12, and PL lamps. For *Pelargonium* it was 13–42% greater under HPS, SL88:12, SSL88:12, SSL70:30, and PL lamps compared to the control. Relative chlorophyll content of *Petunia* and *Tagetes* was 33% and 40%, and 9% and 9% greater for seedlings grown under SSL88:12 and SSL70:30 LEDs, respectively, compared to HPS lamps.

Leaf area.

Leaf area of all species was significantly affected by light treatments (Fig. 2F and G). Leaf area of *Catharanthus*, for instance, was 134%, 40%, and 45% greater for seedlings grown under SSL88:12 LEDs compared to the control, SL88:12, and PL lamps,

respectively. *Impatiens* leaf area was 44% and 75% greater for seedlings grown under HPS lamps and SSL88:12, respectively, than those grown under the control. Leaf area of *Pelargonium* was 49%, 20%, and 24% greater for seedlings grown under HPS lamps compared to the control, SSL88:12, and SSL70:30 LEDs, respectively. *Petunia* and *Tagetes* leaf area was 34%, 30%, and 30%, and 44%, 32%, and 59% greater under HPS, SSL88:12, and PL lamps, respectively, than under the control.

Leaf number.

Leaf number of all species was significantly affected by light treatments (data not shown). For instance, leaf number of *Catharanthus* and *Tagetes* was 40–50%; and 19–21% higher for seedlings grown under HPS, SL88:12, SSL88:12, and SSL70:30 LEDs compared to the control. Leaf number of *Impatiens* and *Petunia* was 26–34% and 32–62% higher for seedlings grown under HPS, SL88:12, SSL88:12, SSL70:30, and PL lamps, respectively, compared to the control. *Pelargonium* leaf number was 18%, 20%, and 31% greater for seedlings grown under HPS, SSL88:12, and SSL70:30 LEDs, respectively, compared to the control.

Root dry mass.

Root dry mass of all species was significantly influenced by light treatments (Fig. 3A and B). For *Catharanthus* and *Pelargonium* it, was 104% and 101%, and 102% and 109% greater for seedlings grown under HPS lamps and SSL88:12 LEDs, respectively, compared to the control. *Impatiens* RDM increased by 93%, 80%, 94%, and 105% for seedlings grown under HPS, SSL88:12, SSL70:30, and PL lamps, respectively, compared to the control. Root dry mass of *Petunia* was 40% and 57% greater under SSL88:12 and SSL70:30 LEDs, respectively, compared to HPS lamps. *Tagetes* RDM was 79–553%

greater for seedlings grown under PL lamps compared to the control, HPS, SL88:12, SSL88:12, and SSL70:30 LEDs.

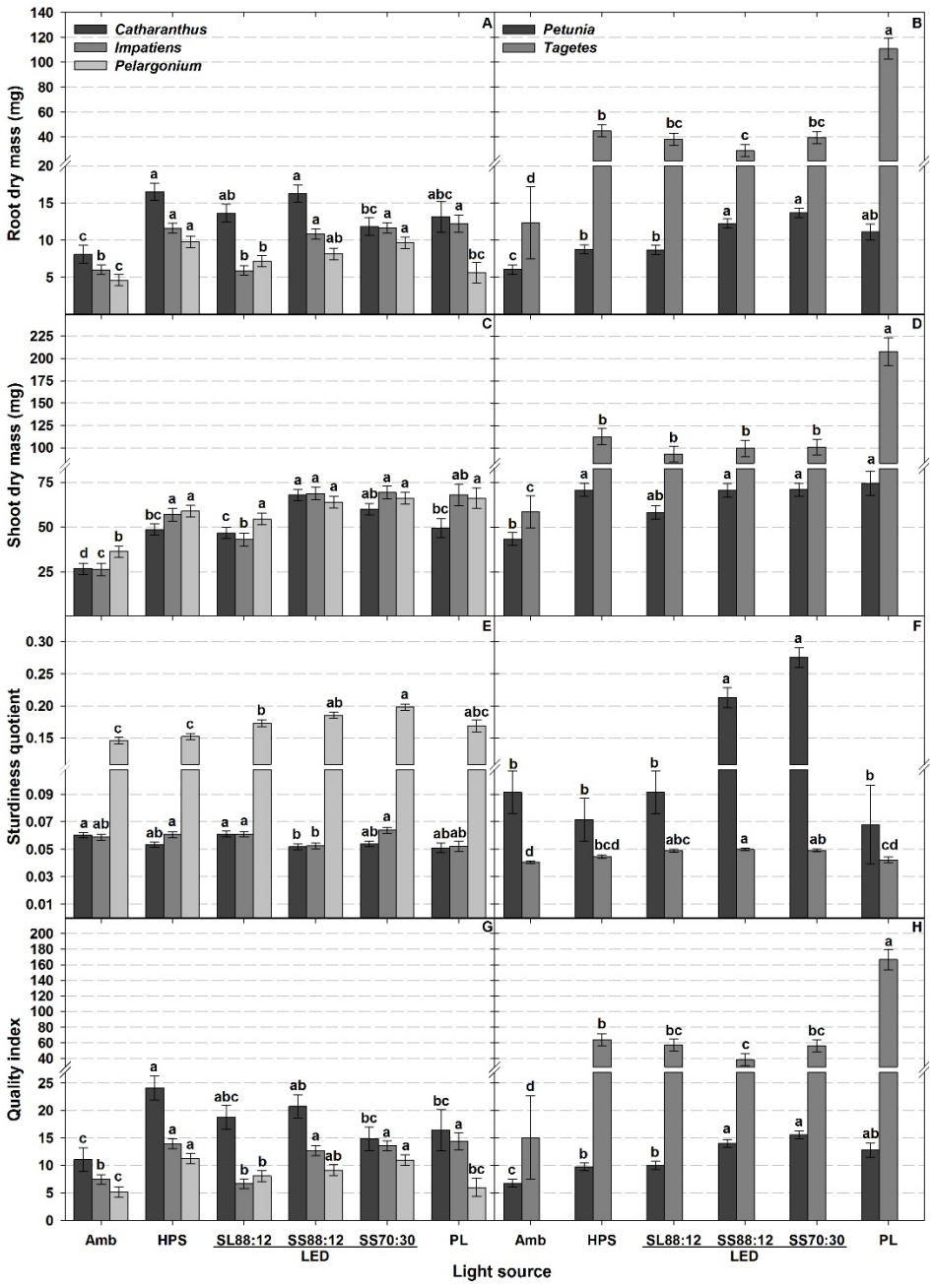

Figure 4.3. (A–H). Effect of ambient solar light (Amb); or 70 µmol·m^{-2}·s^{-1} of supplemental light (SL) delivered from high-pressure sodium (HPS) lamps, light-emitting diodes (LEDs; SL88:12), or plasma (PL) lamps; or 185 µmol·m^{-2}·s^{-1} of sole-source (SS) light delivered from LEDs (SS88:12 and SS70:30) during seedling production on root dry mass, shoot dry mass, sturdiness quotient, and quality index of *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* after 21 or 28 d. Different lower-case letters across treatment source within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Shoot dry mass.

Shoot dry mass of all species was significantly influenced by light treatments (Fig. 3C and D). For example, SDM of *Catharanthus* was 154% and 46% greater for seedlings grown under SSL88:12 LEDs compared to the control and SL88:12 LED, respectively. *Impatiens*, *Pelargonium*, and *Tagetes* SDM was 64–164%, 50–82%, and 59–161% greater under light treatments compared to the control. *Petunia* SDM increased by 62–72% for seedlings grown under HPS, SSL88:12, SSL70:30, and PL lamps compared to the control.

Sturdiness quotient.

Sturdiness quotient was significantly influenced by light treatments for all species (Fig. 3E and F). *Catharanthus* SQ, for example, was 18% greater for seedlings grown under SL88:12 LEDs compared to SSL88:12 LEDs. Sturdiness quotient of *Impatiens* was 16%, 16%, and 22% greater under HPS, SL88:12, and SSL70:30 LEDs, respectively, compared to the SSL88:12 LEDs. *Pelargonium* SQ increased by 36% and 30% under the SSL70:30 LEDs compared to the control and HPS lamps, respectively. Sturdiness quotient of *Petunia* was 133–213% and 201–306% greater for seedlings grown under SSL88:12 and SSL70:30, respectively, compared to the control, HPS, SL88:12, and PL lamps. *Tagetes* SQ was 23%, 12%, and 18% greater for seedlings grown under the SSL88:12 LEDs compared to the control, HPS, and PL lamps, respectively.

Quality index.

Quality index of all species was significantly influenced by light treatment (Fig. 3G and H). For instance, QI of *Catharanthus* was 117% higher for seedlings grown under HPS lamps compared to the control. *Impatiens*, *Pelargonium*, and *Tagetes* QI was 86%

and 81%, 116% and 111%, and 324% and 271% greater under the HPS lamps and SSL70:30 LEDs, respectively, compared to the control. Quality index of *Petunia* increased by 106% and 129% for seedlings grown under SSL88:12 and SSL70:30 LEDs, respectively, compared to the control.

Time to flower.

Time to flower was significantly affected by light treatment for all species (Fig. 4A and B). For example, TTF of *Catharanthus* was reduced by 8, 7, 11, and 12 d for seedlings grown under HPS, SSL88:12, SSL70:30, and PL lamps, respectively, compared to the control. *Impatiens* TTF was delayed by 8–18 d when seedlings were grown under the SSL88:12 LEDs compared to the control, HPS, SL88:12, SSL70:30, and PL lamps, respectively. Time to flower of *Pelaragonium* was reduced by 8 d under PL lamps compared to the control. *Petunia* TTF was reduced by 7 and 16 d for seedlings grown under SL88:12 and PL lamps, respectively, and TTF of *Tagetes* was reduced by 3 and 4 d under SSL88:12 and PL lamps, respectively, compared to the control.

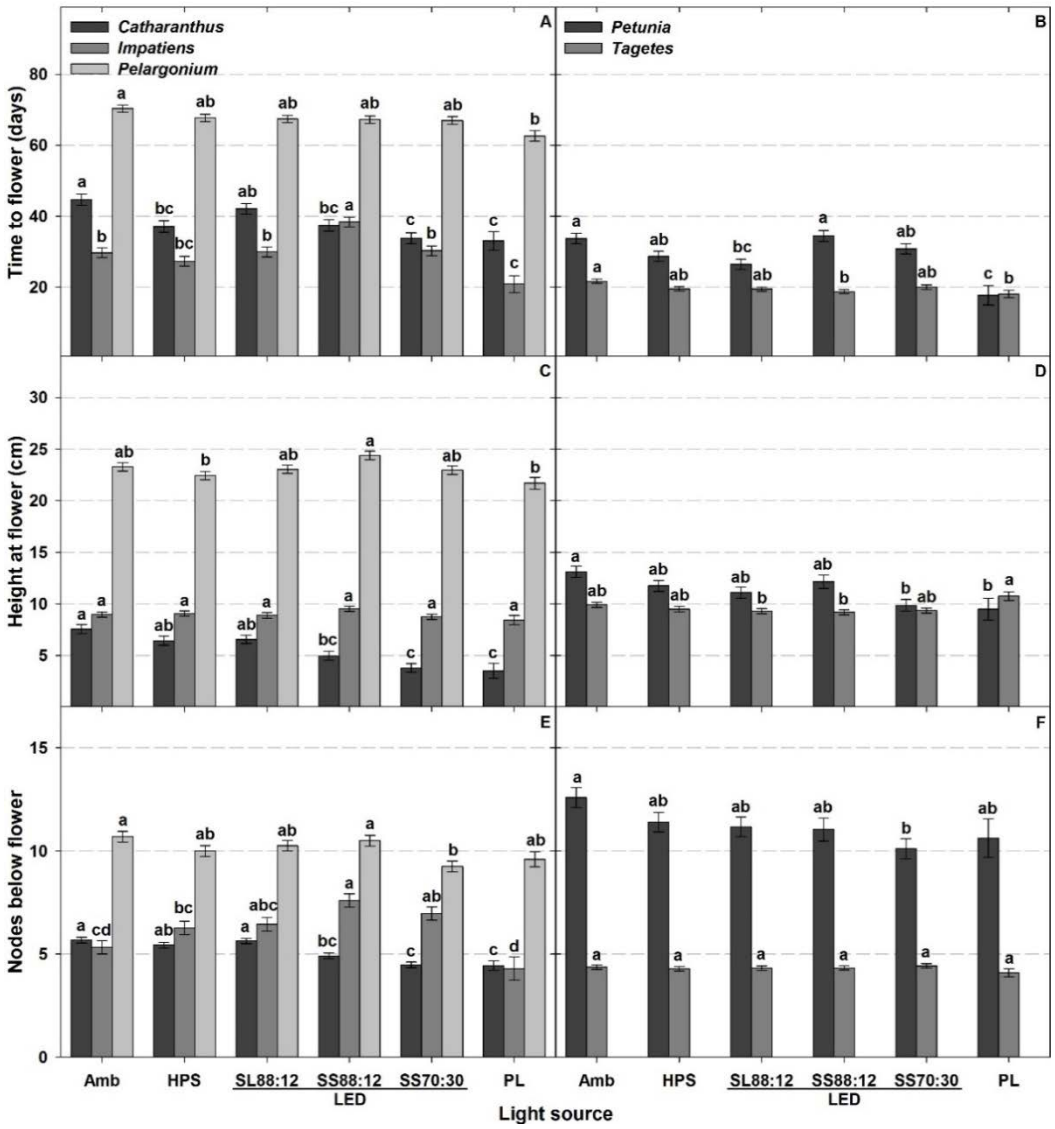

Figure 4.4. (A–F). Effect of ambient solar light (Amb); or 70 µmol·m^{-2}·s^{-1} of supplemental light (SL) delivered from high-pressure sodium (HPS) lamps, light-emitting diodes (LEDs; SL88:12), or plasma (PL) lamps; or 185 µmol·m^{-2}·s^{-1} of sole-source (SS) light delivered from LEDs (SS88:12 and SS70:30) during seedling production on finish time to flower, height at flower, and nodes below flower of *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* after 21 or 28 d. Different lower-case letters across treatment source within a species are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. Each bar represents a mean of 10 plants, and error bars represent SEs of the mean.

Height at flower.

Height at flower of all species with the exception of *Impatiens* was significantly influenced by light treatments (Fig. 4C and D). Height at flower of *Catharanthus*, for instance, was reduced by 34%, 50%, and 54% when seedlings were grown under SSL88:12, SSL70:30, and PL lamps, respectively, compared to the control. *Pelargonium* height at flower was reduced by 8% and 11% under HPS and PL lamps, respectively, compared to the SSL88:12 LEDs. Height of *Petunia* was reduced by 25% and 28% for seedlings grown under SSL70:30 and PL lamps, respectively, compared to the control. Height at flower of *Tagetes* was reduced by 14% and 15% under the SL88:12 and SSL88:12 LEDs, respectively, compared to PL lamps.

Nodes below the first open flower.

The number of nodes below the first open flower was significantly affected by light treatment for *Catharanthus*, *Impatiens*, *Pelargonium*, and *Petunia*, but *Tagetes* was not affected by light treatment (Fig. 4E and F). For example, *Catharanthus* had one fewer node for seedlings grown under SSL88:12, SSL70:30, and PL lamps compared to the control. The number of nodes of *Impatiens* was reduced by two and three nodes under the control and PL lamps, respectively, compared to the SSL88:12 LEDs. *Pelargonium* and *Petunia* had one and two fewer nodes, respectively, for the SSL70:30 LEDs compared to the control.

Discussion

In order for seedlings to withstand shipping and transplanting (Latimer, 1998), they must be compact and fully rooted with a large stem caliper and high RDM (Pramuk and Runkle, 2005). The QI is a tool that integrates morphological parameters such as dry

mass, stem length, and caliper that contribute to a high-quality seedling (Currey et al., 2013). When *Diascia baberae* Hook. f. 'Wink Coral' and *Lantana camara* L. 'Lucky Gold' were grown under DLI that increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$, QI increased 960% and 53%, respectively. The QI of all species in the current study was greater under both SL and SSL compared to the control; and the QI of *Impatiens*, *Pelargonium*, and *Petunia* was similar or greater for seedlings grown under SSL compared to SL treatments. *Tagetes* was the only species where QI was highest under PL lamps compared to the other light treatments. Generally, seedlings of all species grown under SL, SSL, or both were more compact, had a greater stem caliper, leaf area, RDM, SDM, SQ and higher relative chlorophyll content compared to the control.

To demonstrate how DLI influences the quality of seedlings, *Celosia argentia* L. var. *plumosa* L. 'Gloria Mix', *Impatiens* 'Accent Red', *Salvia splendens* Sell ex Roem. & Schult. 'Vista Red', *Tagetes* 'Bananza Yellow', and *Viola* ×*wittrockiana* Gams. 'Crystal Bowl Yellow' were grown for 18 d under a DLI ranging from 4.1 to 14.2 $mol \cdot m^{-2} \cdot d^{-1}$. Shoot dry weight per internode of *Celosia*, *Impatiens*, *Tagetes*, and *Viola* increased 64%, 47%, 64%, and 68%, respectively. *Impatiens* and *Salvia* height also decreased by 27% and 37% (Pramuk et al., 2005). Similarly, in the current study, height of *Pelargonium*, *Petunia*, and *Tagetes* was reduced by 13% and 18%, 62% and 69%, and 13% and 11% for seedlings grown under the SSL88:12 and SSL70:30 LEDs compared to the control, resulting in more compact seedlings. Shoot dry mass of *Catharanthus*, *Impatiens*, *Pelargonium*, and *Tagetes* increased 74–154%, 64–164%, 60–82%, and 59–161%, respectively, for seedlings grown under all light treatments compared to the control.

Similarly, in the current study, RDM increased by 44–127% and 136–553% for *Petunia* and *Tagetes* seedlings, respectively, grown under SL and SSL light compared to the control. A separate study quantified how SL during cutting propagation influences rooting and subsequent growth of *Impatiens hawkeri* Bull. 'Celebrette Red', 'Harmony Magenta', and 'Harmony White' and *Petunia* ×*hybrida* hort. Vilm.-Andr. 'Double Wave Spreading Rose', 'Supertunia Mini Purple', and 'Tiny Tunia Violet Ice'. As propagation DLI increased, rooting, root dry mass, and shoot dry mass increased while subsequent time to flower decreased. For instance, after 16 d of propagation, root and shoot dry mass of *I.* 'Celebrette Red', 'Harmony Magenta', and 'Harmony White' increased by 580%, 604%, and 867% and 40%, 32%, and 53%, respectively, as DLI 1.6 to 10.7 $mol \cdot m^{-2} \cdot d^{-1}$. Additionally, average root dry mass of *P.* 'Double Wave Spreading Rose', 'Supertunia Mini Purple', and 'Tiny Tunia Violet Ice' increased by 506%, 2395%, and 680%, respectively, and shoot dry mass increased by 108%, 147%, and 106%, respectively, as average DLI increased from 1.2 to 9.5 $mol \cdot m^{-2} \cdot d^{-1}$ (Lopez and Runkle, 2008).

Leaf area and number of all species was similar or greater under SL compared to the control, or SSL treatments compared to SL. Similarly, a separate study demonstrated that leaf area of *Lactuca sativa* L. 'Sunmang' and 'Grand Rapid TBR' increased by 325% and 324%, respectively, for plants grown under increasing proportions (%) of red:blue LEDs ranging from 41:59 to 100:0 delivering a 12-h photoperiod of 171 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (DLI ≈7.4 $mol \cdot m^{-2} \cdot d^{-1}$) in growth chambers. Conversely, as the proportion of blue light increased up to 47%, relative chlorophyll content increased ≈140% for 'Sunmang' and relative chlorophyll content of 'Grand Rapid TBR' also increased for treatments receiving proportions of blue light greater than 26% (Son and Oh, 2013). Similarly, our

results show that relative chlorophyll content of *Catharanthus*, *Impatiens*, *Pelargonium*, *Petunia*, and *Tagetes* was 16%-25%, 20%-47%, 13%-21%, 28%-84%, and 10%-21% greater under SL and SSL compared to the control.

Time to flower varied among species. For instance, TTF of *Catharanthus* decreased by 7–12 d for seedlings grown under HPS, SSL88:12, SSL70:30, and PL lamps compared to the control. However, *Impatiens* seedlings grown under the SSL88:12 LEDs were delayed up to 18 d compared to other treatments; while TTF of *Petunia* seedlings grown under SL or SSL was similar to or reduced compared to the control. Another study compared seedlings of *Petunia* 'Madness Red' and *Viola* 'Delta Premium Yellow' grown under SL of 90 $\mu mol \cdot m^{-2} \cdot s^{-1}$ or 3 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of photoperiodic lighting from HPS lamps in a greenhouse. Time to flower of both *Petunia* and *Viola* was reduced when seedlings received SL during the second, third, or both seedling stages compared to photoperiodic lighting. For instance, TTF of *Petunia* and *Viola* was reduced by 4.7 and 5.7 d, respectively, when seedlings received SL during the latter-two third seedling stages compared to seedlings grown under photoperiodic lighting (Oh et al., 2010).

Similarly, Hutchinson et al. (2012) showed that increasing DLI during cutting propagation of *Angelonia angustifolia* Benth. 'AngelMist White Cloud', *Nemesia fruticans* (Thun.) Benth. 'Aromatica Royal', *Osteospermum ecklonis* (DC.) Norl. 'Voltage Yellow', and *Verbena ×hybrida* Ruiz 'Aztec Violet' reduced TTF. For example, as propagation DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$, TTF of *Angelonia* and *Osteospermum* was reduced by 23 and 19 d, respectively. Additionally, height at flowering decreased by 6.1 and 3.5 cm for *Angelonia* and *Osteospermum*, respectively, as propagation DLI increased from 1.2 to 12.3 $mol \cdot m^{-2} \cdot d^{-1}$. Conversely, our study found no

significant difference in *Impatiens* finish height; however, height of *Catharanthus*, *Pelargonium*, *Petunia*, and *Tagetes* was similar or reduced under all light treatments compared to the control.

Although energy consumption was not a central focus of this study, it does merit discussion. In the greenhouse, HPS, LEDs, and PL lamps used 5.5, 3.4, and 8.9 $kWh \cdot d^{-1}$. As a result, the LEDs used 38% and 62% less electricity than HPS and PL, respectively, to grow 10 trays of seedlings. Another study used forced-air cooled LEDs where fans accounted for 37% to 45% of the energy consumed by the arrays, resulting in energy consumption 9% to 35% greater than HPS lamps (Currey and Lopez, 2013). Conversely, a different study found that passively cooled LEDs (85:15 red:blue) used ≈55% less electricity than HPS lamps, but blocked solar radiation by ≈50% (Randall and Lopez, 2014). In contrast, the LEDs used in this study only blocked solar radiation by ≈5%, resulting in a minimal reduction of solar radiation that reached the seedlings.

The QI of all species was similar or higher for seedlings grown under SL compared to the control; and similar or higher for seedlings grown under SSL compared to the greenhouse. Additionally, seedlings of *Impatiens*, *Pelargonium*, and *Petunia* grown under SSL had a QI similar or greater than seedlings grown under SL. However, the QI of *Catharanthus* was reduced under the SSL70:30 LEDs compared to HPS lamps, *Tagetes* was reduced under SSL88:12 compared to HPS and PL lamps. Additionally, TTF of all species except *Impatiens* was similar or reduced under SL and SSL treatments compared to the control. Therefore, the use of LEDs for SL in the greenhouse with a 88:12 red:blue light ratio could be used as an alternative to HPS lamps. Additionally, LEDs could be used for SSL in vertical growth chamber production systems as an

effective alternative to greenhouse production systems for annual bedding plant seedling production.

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